TECHNICAL REPORT II

STUDY OF CONCEPTS FOR NAVY TACTICAL VOICE COMMUNICATIONS (U)

PREPARED BY

R. V. JANC

B. I. MARKS

N. T. THOMOPOULOS

IIT RESEARCH INSTITUTE
10 West 35 Street
Chicago, Illinois 60616

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Robert V. Janc
Barry I. Marks
Nickolas T. Thomopoulos

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13. ABSTRACT

The objective of this program was to formulate and develop an analytical model based on queueing theory for the purpose of evaluating various tactical voice net configurations and signaling alternatives. Results presented from the analytic queueing model are presented here in the context of specific Naval tactical net situations. The results illustrate only the use of the methodology developed; consequently, mathematical derivations have been omitted with the exception of a brief technical summary. Specifically, those areas examined are mutual signaling interference, multiple access-discrete address (MADA) systems, preemptive/non-preemptive priority, busy signal, hold call and non-Poisson statistics. For each of these, various performance measures (e.g., Grade of Service) are illustrated graphically as functions of net utilization.

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FOREWORD

This Technical Report was developed under Contract N00014-70-C-0375 for Code 462 of the Office of Naval Research as IIT Research Institute Project E6174. Results derived from the analytical queueing model are presented here in the context of specific Naval tactical net situations. The results are intended to illustrate only the use of the methodology which has been developed; consequently, mathematical derivations have been omitted with the exception of a brief technical summary. Supporting mathematical derivations will be presented in a subsequent report.

The support and assistance of the Scientific Officer for this program, CDR Robert McCaffery of Code 462 in ONR is gratefully acknowledged. The results reported reflect the major contributions made by Dr. N. Thomopoulos and Mr. B. Marks. The contribution of Dr. S. Tsai is also appreciated.

Respectfully submitted,

IIT RESEARCH INSTITUTE

Robert V. Janc

Dr. Robert V. Janc
Project Engineer
Communications Systems

APPROVED:

John E. McManus

John E. McManus
Acting Manager
Communications Systems

James J. Krstansky

James J. Krstansky
Assistant Director of Navy Programs
Electronics Research Division

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1. INTRODUCTION AND SUMMARY

1.1 Introduction

The principal objective of this program is the development of an analytic methodology based on queueing theory for study of Naval radio tactical voice communication nets with various alternatives for signaling, frequency assignment and control. The purpose of this report is to provide a summary of the work conducted since the previous technical report.[1] It is not intended to document the mathematics; this will be done in a subsequent report. Rather, this report is intended to be a detailed but brief account of the results obtained thus far. The method selected for doing this is application of the methodology to specific tactical net situations. Two examples of such situations are signaling errors due to mutual interference and comparison of discrete nets with a multiple access-discrete address system having a number of nets. As a result of application of the methodology to specific tactical net situations, certain conclusions concerning performance were drawn. The most significant conclusions are listed at the end of this section.

Before summarizing it is necessary to provide a basic but brief* orientation with respect to the terminology used. What is being considered is a group of tactical Naval communication stations with common tactical operational functions comprising a tactical voice radio network. This is referred to simply as a net. Each of the stations is a physical location (i.e., CIC on a ship or the cockpit of an aircraft) with a radio operator. The purpose of the operator <u>from the viewpoint</u> of the analytic model is to transmit and receive messages.

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*A complete list of definitions are provided in the Glossary.

For each station of the net and the net itself, certain fundamental input parameters are used to characterize the activities; they are:

- λ - the rate at which all messages are generated for transmission in the net.
- μ^{-1} - the average message time duration.
- ρ - the net utilization which can be interpreted as the average number of messages being transmitted on all frequencies used by the stations of the net ($\rho = \lambda\mu^{-1}$).
- S - the number of stations in a net.

In addition, certain performance measures are used; they are:

- Grade of Service - probability an operator will encounter a delay given he wishes to send a message. (The probability an operator will encounter a delay becomes better as it gets smaller, therefore a Grade of Service of zero is the best.)
- Mean Access Delay - the average time for an operator to get on the air given he has encountered a delay.
- Average Number of Messages in the Net Queue - the average number of messages which are being delayed.
- Mean Waiting Time in the Net Queue - an indication of the time a message is delayed even if the operator at a station isn't delayed (e.g., an operator desires to send two messages; the first message is sent immediately but the second is delayed since it must wait for the first message transmission to be completed).

It is important to observe that the first two performance measures are related to the operator and the second two to the efficiency of message transfer within the net.

1.2 Program Accomplishments and Report Organization

A unified methodology has been developed on the basis of a single queueing model. The model utilizes as inputs the particular net structure to form a queueing discipline and message traffic information to form the input statistics. The information outputs from the model are individual operator access and net performance. It appears that almost any net situation that can be physically structured can also be conceptually handled by the model. It is important to note that there are limitations on complexity. These are strictly functions of the techniques used to obtain quantitative results.

This report is divided into two parts. Section 2 is mathematical in nature and provides an overall technical summary. Sections 3 through 8 utilize examples to describe the application of the methodology.

1.3 Conclusions

In Sections 3 through 8 a number of conclusions and observations have been made. Most of these are rather specific and will not be enumerated here; however, a number of the more significant conclusions will be presented.

- A single frequency net employing asynchronous signaling exhibits a severe performance degradation at approximately 0.65 net utilization. It is important to note that as a result of physical constraints a net with voice signaling is asynchronous.
- When a number of discrete nets are organized into a multiple access-discrete address (MADA) system,

a number of improvements result. Their magnitude is a function of the number of nets and their respective utilization. In general, Grade of Service is significantly improved and a frequency spectrum savings is possible.

- Any frequencies saved in conversion to MADA present an alternative to preempt. The extra frequency or frequencies could be used for high priority messages. This would eliminate the requirement for special signaling equipment.

- Hold call appears to provide little change in net performance or operator convenience. This is intuitively attributed to two factors; first, operators not only get rid of messages by using hold call but also receive them; and second, at low utilization hold call is seldom required while at high utilization an operator is more likely to encounter a busy frequency than a busy station.

- In a net with preemptive signaling the percentage of messages that are preemptive should be kept less than 5 percent to avoid severe degradation in net performance at medium utilization levels ($0.3 < \rho < 0.6$). The severe degradation is attributed to some messages being preempted more than once.

- Improvements achieved with non-preemptive priority signaling can also be achieved or exceeded by incorporating MADA. It is important to note that with MADA performance is improved for all messages while with priority only a fraction of the messages experience a performance improvement.

It is important to note that these conclusions are based primarily on the examples used in this report for particular net situations and should not be applied to net situations which deviate significantly from the examples used here. In those cases the methodology should be utilized to obtain numerical results for the situation of interest.

2.0 TECHNICAL SUMMARY

2.1 Introduction

During the initial phase of the program a model was developed to characterize a tactical radio communication net. The model was used to evaluate several tactical net alternatives. Examples of the alternatives are frequency assignment, digital signaling and special signaling features (preempt). The method selected for evaluation was to obtain a closed form mathematical relationship for various performance measures in terms of specific net parameters. As the program progressed and more complex configurations were addressed it became apparent that, using the mathematical techniques* considered up to that time, the problems would soon be too complex to obtain a solution. It was therefore necessary to find new techniques for evaluating complex tactical net configurations.

This section of the report describes the current method of evaluating performance for a particular tactical net configuration. The method has been applied in the same way for all configurations addressed and it appears that conceptually, any tactical net configuration which can be physically structured can also be handled by the method. It is important to note that there are limitations on the system complexity. These are strictly functions of the techniques used to obtain numerical results.

Because the same approach was used on all of the tactical net configurations considered thus far, and because this report is intended to be more of a summary of results rather than a documentation of the mathematics, the technical summary is general in nature. With the exception of some examples, no specific details of any of the mathematics for the net configurations considered will be given. Documentation for the

*e.g., generating functions

mathematics will be contained in a subsequent report.

2.2 Generalized Model

Previously the model was considered unique for each net configuration that was addressed. This uniqueness was a result of the equations for each net configuration being unique. Primarily due to the unified mathematical approach which has been developed and applied thus far, it is now possible to consider a single generalized model which is applicable to all of the net configurations considered and has potentially an even broader scope.

Figure 2.1 illustrates the concept of the generalized model. The model itself is represented by the center box and is referred to as the Calling System - Outer System model. Details of the model are illustrated in Fig. 2.2 and were discussed in the previous technical report.[1*] To review briefly, a station in a net is partitioned into an "outer system" and a "calling system." At most one message can be in the calling system at any one time. If more than one message is at the station, one is in the calling system and all others are in the outer system. Within the calling system are two more partitions, the "calling queue" and "station calling." If a message is in the calling system it is either in the station calling partition or the calling queue partition. The station calling partition represents the action of transmitting a message. The reason for allowing only one message in the station calling system reflects the observation that the operator is either transmitting a message or waiting to transmit a message.

Referring again to Fig. 2.1, the model has two inputs and one output. The first input is the Queueing Discipline and is determined by the net configuration. Strictly speaking the

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*All references are listed at the end of this report.

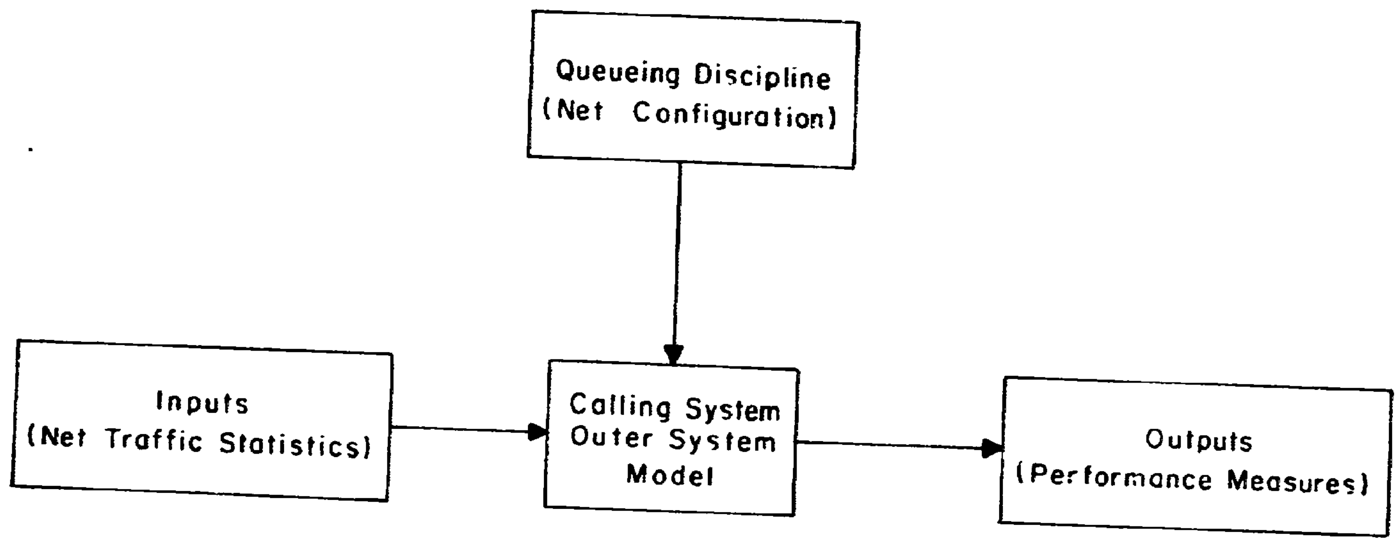

Fig. 2.1 GENERALIZED MODEL CONCEPT

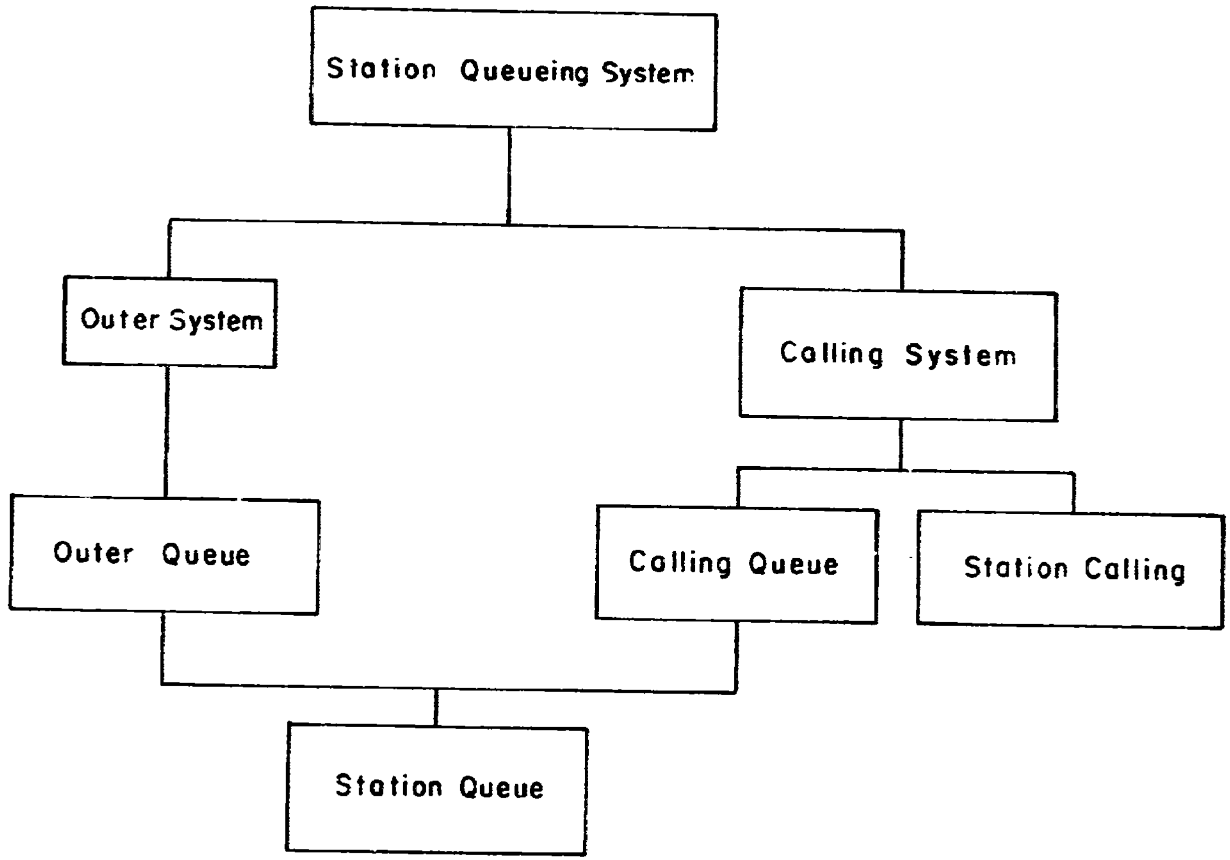

Fig. 2.2 CALLING SYSTEM - OUTER SYSTEM MODEL

model is mathematically characterized in terms of a Markoff process.* The Markoff process is specified by various states and a state transition probability matrix. These are determined on the basis of the physical net configuration. Another way of viewing this is to consider a linear electrical network. Although the network elements can be connected in various ways and have different values, the network can always be represented by a set of linear differential equations. This model, thus far, can be represented by a set of linear difference equations.

The second input is the net traffic statistics. Thus far it has been assumed that these statistics are Poisson in nature; that is messages are generated at times specified by a Poisson process and have durations determined by an exponential density function. Although nearly all of the net configurations thus far have utilized Poisson statistics, other types of statistics can also be employed by this model. An example of a net in which messages are generated with Erlangian statistics is given in Section 8 of this report. In addition to Erlangian statistics, hyperexponential statistics can also be conveniently used. A large number of statistical distributions can also be approximated in terms of the Erlangian and hyperexponential distributions. There is one important point to note; thus far only traffic statistics in which messages are generated independently can be used. An attempt will be made to remove this restriction during the next portion of the program.

The principal outputs from the model are the performance measures. Although there is a great deal of information available from the model, four measures have been selected that reflect two factors in net operation: first the effectiveness

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*This is true for the net configurations considered thus far but could be changed to a more general stochastic process.

of the net for the various operators and second, the efficiency of message flow within the net.

To illustrate the use of the generalized model concept the remainder of this section will demonstrate through example, the way in which the queueing discipline is structured, the input statistics are fixed, the performance measures defined and numerical results obtained. This will be done for a single frequency net with mutual signaling interference as a possible problem.

2.3 Input Statistics

For the example selected, Poisson message generation statistics and exponential message length statistics are assumed. The impact of this assumption can be summarized in the following three postulates and one corollary:

- If h represents an infinitesimal time interval then the probability that exactly one message is generated in the system in time interval $(t, t + h)$ is $\lambda_n h + 0(h)$ when the system is in state $E_n (n = 0, 1, 2, \ldots)$. The constant λ_n is the average message generation rate for the system. The term $0(h)$ is the sum of all terms negligible compared to $\lambda_n h$. Quantitatively,

$$\lim_{h \to 0} 0(h)/h = 0$$

- The probability that exactly one message transmission ends in the system in time interval $(t, t + h)$ is $\mu_n h + 0(h)$ when the system is in the state $E_n (n = 1, 2, \ldots)$. The constant μ_n^{-1} is the average message length.

- The probability that the number of message generations and message transmissions ending will exceed

one in the time interval $(t, t + h)$ is $0(h)$ when the system is in state $E_n (n = 0, 1, 2, \ldots)$.

From the three postulates the following corollary results directly:

- The probability that neither a message generation nor an end of transmission occur in time interval $(t, t + h)$ is $1 - \lambda_n h - \mu_n h + 0(h)$ when the system is in the state $E_n (n = 1, 2, \ldots)$.

It is important to note that although the Poisson postulates have been stated in terms of single subscripted states (E_n), they apply in the same way to multiply subscripted states.

2.4 Queueing Discipline and Net Configuration

The first step in establishing the queueing discipline is to define the appropriate states. For the problem of mutual signaling interference those states are defined as follows:

E_{00} = No messages are being transmitted and there are no messages in the net.

E_{1n} = A message is being transmitted and there are n messages in the net.

E_{2n} = Mutual interference is occurring and there are n messages in the net.

These states were the ones selected for this example. They do not represent the only possible selection; in any case the end results should be the same if the queueing discipline truly reflects the net configuration.

The next step is to establish a set of difference equations in terms of the state probabilities and state transition probabilities. To accomplish this consider the physical process of mutual signaling interference. Assume that the system is in state E_{1n} with $n \geq 3$. When the message in transmission ends

the two* or more operators having messages will attempt to signal. With some probability (α_n) that depends on the number of operators trying to signal, a mutual interference situation will result and the system will enter the state $E_{2,n-1}$ (n-1 since one message left the system when transmission ended). Since the interference was present the various stations will have to signal again to establish a call.

The first time signaling occurred each operator was "synchronized" to the end of the previous transmission. If signaling interference was present the operators would have to try and signal again; however, this time they would not be "synchronized" and the probability of mutual interference would no longer be α_n but γ_n where

$$\gamma_n < \alpha_n \tag{2.1}$$

The probability γ_n would then be used for all subsequent signaling attempts until a call was established. The difference equations can then be written as follows:

$$P_{00}(t + h) = (1 - \lambda h) P_{00}(t) + \mu h P_{11}(t) \tag{2.2}$$

$$P_{11}(t + h) = (1-\lambda h-\mu h) P_{11}(t) + \mu h P_{00}(t) + \mu h P_{12}(t) \tag{2.3}$$

and

$$P_{1n}(t + h) = (1-\lambda h-\mu h) P_{1n}(t) + \lambda h P_{1,n-1}(t)$$
$$+ (1-\alpha_n) \mu h P_{1,n+1}(t) + (1-\gamma_n) \beta \mu P_{2n}(t) \tag{2.4}$$

$$P_{2n}(t + h) = (1-\lambda h-\beta \mu h) P_{2n}(t) + \lambda h P_{2,n-1}(t)$$
$$+ \alpha_n \mu h P_{1,n+1}(t) + \gamma_n \beta \mu P_{2,n}(t) \tag{2.5}$$

*When n = 2 it is probable that these two messages are in separate stations but not certain. This detail will not be discussed here but is taken into account in the final result.

where λ is the average message generation rate, μ^{-1} is the average message length and $(\beta\mu)^{-1}$ is the average interference length. These equations would then be converted to equilibrium equations by the methods outlined in the previous technical report[1] in Section A.4.1.

2.5 Performance Measures and Net Configurations

Extreme care must be taken in evaluating and interpreting the performance measures for the various net configurations considered. For example consider the Grade of Service. It is defined as the probability that an operator at station i will encounter a delay when sending a message. Previously[1] this was defined in terms of the calling system - outer system model as

$$GS(i) = \frac{P_{cq}(i)}{P_{cs}(i)} \tag{2.6}$$

where $P_{cq}(i)$ is the probability of being in the calling queue at station i and $P_{cs}(i)$ is the probability of being in the calling system at station i. The equation is valid as long as the only delay in the calling system occurs in the calling queue. This is not true for the case of mutual interference. In that case the operator is also delayed when he is calling with interference. Equation (2.6) must be modified for that case as follows:

$$GS(i) = \frac{P_{cq}(i) + P_{c2}(i)}{P_{cs}(i)} \tag{2.7}$$

where $P_{c2}(i)$ is the probability that an operator is signalling with interference at station i. Note that

$$P_{cs}(i) = P_{cq}(i) + P_{c2}(i) + P_{c1}(i) \tag{2.8}$$

where $P_{c1}(i)$ is the probability that an operator is transmitting a message at station i.

Three other performance measures were also defined. They are the Mean Access Delay $W_A(i)$, the Expected Number of Messages in the Net Queue L_q and the Mean Waiting Time in the Net Queue W_q. Care must also be exercised in defining them. To illustrate this point their previous[1] definitions will be given and their definitions for the example considered here.

Table 2.1

Performance Measures

Performance Measure	One Frequency Net	One Frequency Net (Interference)
$W_A(i)$	$\frac{P_{cs}(i)}{GS(i)}$	$\frac{P_{cs}(i) + P_{c2}(i)}{GS(i)}$
L_q	$L - L_{c1} - L_{c2}$	$L - L_{c1}$
W_q	$\frac{L - L_{c1} - L_{c2}}{\lambda}$	$\frac{L - L_{c1}}{\lambda}$

It should be apparent from the previous example that the definitions for the performance measures are dependent upon the net configuration. Because of this the significance of comparing two net configurations cannot be fully understood unless the performance measure definitions are explicitly stated in terms of both net configurations.

2.6 Matrix Solutions

The performance measures are defined in terms of the various partition probabilities of the calling system - outer system model. These partition probabilities can in turn be defined in terms of the system state probabilities. For example for the single frequency net with mutual interference

$$L_q = L - L_{c2} \tag{2.9}$$

substituting

$$L_q = \sum_{n=1}^{\infty} n(P_{1n} + P_{2n}) - \sum_{n=1}^{\infty} P_{1n} \tag{2.10}$$

Therefore the problem reduces to one of evaluating the system state probabilities.

The equilibrium equations for the system can be expressed as a set of equilibrium matrix equations as follows:

$$\bar{A}_0 \bar{P}_0 = \bar{C}_0 \bar{P}_1 \tag{2.11}$$

$$\bar{A}_1 \bar{P}_1 = \bar{B}_1 \bar{P}_0 + \bar{C}_1 \bar{P}_2 \tag{2.12}$$

$$\bar{A}_n \bar{P}_n = \bar{B}_n \bar{P}_{n-1} + \bar{C}_n \bar{P}_{n+1} \qquad n \geq 2 \tag{2.13}$$

where the $\bar{P}$ matrices are column matrices, the $\bar{B}$ matrix is the message generation matrix, the $\bar{C}$ matrix is the end of transmission matrix and the $\bar{A}$ matrix is a no change of state matrix. Equations (2.11) through (2.13) represent the lower degenerate system equations and the general equations. In addition to these equations upper degenerate equations also exist. This is not easily seen since the equations only exist when the system of equations is expressed as a limit.

Assume that the maximum number of messages in the system is finite and equal to L. Then another matrix equation can be added to the existing matrix equations. It is given by

$$\bar{A}_L \bar{P}_L = \bar{B}_L \bar{P}_{L-1} \tag{2.14}$$

and can be considered as the upper degenerate matrix equation for the system. The original system was an infinite queue system; Eqs. (2.11) through (2.14) represent a finite queue system. However Reuter and Ledermann[2] have shown that as the

maximum number of messages in the system L is allowed to go to infinity, the solution of the finite queue system will converge to the solution for the infinite queue system.

In evaluating the state probabilities it is not necessary to have L tend to infinity. The solution converges fast enough such that a moderate value of L will yield adequate numerical results. Therefore the problem reduces to solving a finite set of simultaneous linear matrix equations.

2.7 Numerical Evaluation

Each of the L matrix equations can be considered as $\ell(n)$ linear algebraic equations where $\ell(n)$ can be a function of the number of messages in the system. In general this means that the system is represented by

$$L_T = \sum_{n=1}^{L} \ell(n) \qquad (2.15)$$

linear algebraic equations.* The obvious way to solve the system of equations is to invert the L_T by L_T system matrix; however, that matrix can become quite large (e.g., $L_T > 1000$) and the computer cost would become prohibitive.

Because of the characteristics of the system of equations there is a more economical method that can be used to obtain numerical results. Consider Eq. (2.14), it can be rewritten as

$$\bar{P}_L = \bar{A}_L^{-1}\bar{B}_L\bar{P}_{L-1} \qquad (2.16)$$

Defining

$$\bar{F}_L = \bar{A}_L^{-1}\bar{B}_L \qquad (2.17)$$

*The n = 0 equation is linearly dependent and is not necessary for a solution.

then

$$\bar{P}_L = \bar{F}_L \bar{P}_{L-1} \tag{2.18}$$

The next equation (n = L-1) can then be written as

$$\bar{A}_{L-1} \bar{P}_{L-1} = \bar{B}_{L-1} \bar{P}_{L-2} + \bar{C}_{L-1} \bar{P}_L \tag{2.19}$$

or

$$\bar{P}_{L-1} = (\bar{A}_{L-1} - \bar{C}_{L-1} \bar{F}_L)^{-1} \bar{B}_{L-1} \bar{P}_{L-2} \tag{2.20}$$

Defining

$$\bar{F}_{L-1} + (\bar{A}_{L-1} - \bar{C}_{L-1} \bar{F}_L)^{-1} \bar{B}_{L-1} \tag{2.21}$$

then

$$\bar{P}_{L-1} = \bar{F}_{L-1} \bar{P}_{L-2} \tag{2.22}$$

Generalizing

$$\bar{P}_n = \bar{F}_n \bar{P}_{n-1} \qquad 1 \leq n < L \tag{2.23}$$

Where

$$\bar{F}_n = (\bar{A}_n - \bar{C}_n \bar{F}_{n+1})^{-1} \bar{B}_n \qquad 1 \leq n < L \tag{2.24}$$

All of the probability vectors can be specified in terms of $\bar{P}_0$ as follows:

$$\bar{P}_n = \prod_{i=n}^{1} \bar{F}_i \bar{P}_0 \tag{2.25}$$

Utilizing the last remaining equation

$$\sum_{n=0}^{L} \bar{1}_R(n) \bar{P}_n = 1 \tag{2.26}$$

the state probabilities can be determined exactly. The matrix $\bar{1}_R(n)$ is the unity row matrix and has the same number of elements as the $\bar{P}_n$ column matrix.

The solution technique involves multiplication and inversion of much smaller matrices. The savings achieved by using it as opposed to system matrix inversion is of the order

$$1 - (\ell(L)/L_T)^3 \tag{2.27}$$

in terms of computer time. In addition complex systems with system matrices that are too large for computer inversion can be handled using this technique.

3. MUTUAL SIGNALING INTERFERENCE

3.1 Introduction

Up to the present point in time the results have been idealized to some extent. A specific area where this has been done is that of signaling or establishing a call. For all of the net configurations used to date the system equations have been structured on the implicit assumption that there is no possible mutual interference in the net. Specifically, when two or more operators are attempting to establish a call, it has been assumed that one of them would always succeed on the first attempt.

There are two approaches which can be taken in the design of a signaling system for a net. In the first the signaling equipment is designed to operate synchronously. The purpose for doing this is to reduce to a negligible amount the probability of mutual signaling interference. For this particular design scheme the results given thus far apply strictly.

The second design approach involves asynchronous operation of the signaling equipment. Clearly under this design scheme there is a finite and not insignificant probability of mutual signaling interference. It is the purpose of this section of the report to illustrate the impact of asynchronous signaling on a tactical voice net. In addition the range of validity for the results in which mutual interference was not considered will be discussed in the context of a net with mutual signaling interference.

3.2 Scope of Application

A queueing discipline has been structured which characterzes a single frequency tactical voice net operating with asynchronous signaling. The method of signaling may be voice or digital. There can be S stations in the net where S may

range from three to an arbitrarily large number. Each of the stations in the net is characterized by two parameters. They are $\lambda(i)$, the average message generation rate at station i and $\mu(i)^{-1}$, the mean message length at station i. Within one constraint the values of $\lambda(i)$ are arbitrary; the values of $\mu(i)$ are all equal to μ. The single constraint is

$$\sum_{i=1}^{S} \frac{\lambda(i)}{\mu} = \sum_{i=1}^{S} \rho(i) = \rho < 1 \qquad (3.1)$$

where $\rho(i)$ is the utilization at station i and ρ is the net utilization. Poisson message generation and exponential message length have been assumed.

In structuring the queueing discipline the following net operation was assumed. When a message in transmission ends and there are two or more stations waiting to use the frequency, all of the waiting stations will attempt to call-up. Because the stations' call-ups are in a sense synchronized to the end of the previous transmission, there will be a probability α_n that they will interfere with each other and result in an unsuccessful call-up. This probability will be a function of the number of messages in the system. If the initial call-ups of the stations involved are all unsuccessful, then they will attempt another call-up. These call-ups will not be synchronized as were the initial ones; therefore a different probability γ_n will be required to determine if there was mutual interference and the call-ups were again unsuccessful. In general

$$\gamma_n < \alpha_n \qquad (3.2)$$

The probability γ_n will be used for all subsequent call-up attempts until a call is established.

The call-up signal which is not successful because of mutual interference still utilizes time on the frequency. It is necessary to account for this time. To accomplish this the

mutual interference is assumed to be of finite time duration which is exponentially distributed with mean duration $(\beta\mu)^{-1}$. The constant β will in general be greater than one. Its actual value would depend on the type of signaling (voice or digital), the average message length μ^{-1} and the signaling format.

One additional factor was included in the queueing discipline. This factor takes into consideration the probability of signaling error due to the radio propagation media when mutual interference is not present. For example when only one station is signaling there will be no mutual interference.

3.3 Description of Results

To illustrate the impact of mutual signaling interference a comparison of the performance of two nets will be presented. It will be assumed that both nets have digital signaling. Also, both nets have twelve stations and each station has the same average message generation rate and average message length. The average message length for the nets is assumed to be 20 seconds and the average time duration of mutual interference when present is assumed to be 1 second (i.e., $\beta = 20$). The only difference in the two nets is that one has synchronous signaling and the other has asynchronous signaling.

The performance measures used to compare the two nets are for operator access the Grade of Service and Mean Access Delay; for net performance the Average Number of Messages in the Net Queue and the Mean Message Waiting Time in the Net Queue. These measures are all averages. To avoid any confusion in the meaning of each of the performance measures they will be explained explicitly for each net. The Grade of Service is the probability that an operator wishing to send a message encounters a delay. For the synchronous net the delay occurs when the operator encounters a busy frequency. For the asynchronous net

it also occurs when he encounters mutual interference. In both cases the respective delays are referred to as the Mean Access Delay. The Average Number of Messages in the Net Queue for the synchronous net are all messages in the net except the one on the frequency. For the asynchronous net it also includes those on the frequency that are experiencing mutual interference. The average time these messages must wait is the Mean Message Waiting Time in the Net Queue.

The four performance measures have been illustrated in Figs. 3.1 and 3.2 for both nets as a function of net utilization. The Mean Access Delay and Net Queue Waiting Time have been plotted with μ normalized to one. From the curves the following observations are made:

- For net utilization less than 0.4 there is no significant difference between the two nets in terms of performance.
- For net utilizations greater than 0.6 net performances diverge sharply with the net having mutual interference having poorer performance.

The results illustrated in the figures are exactly what would be intuitively suspected. Under conditions of high net utilization the interference problem in the asynchronous net becomes so severe as to "lock up" the entire net such that it breaks down completely. This degradation in net performance has also been verified experimentally[3] during a previous and independent program.

3.4 Conclusions

From the numerical results and physical considerations it is possible to draw a number of conclusions concerning the interference problem and the interpretation of other results. They are as follows:

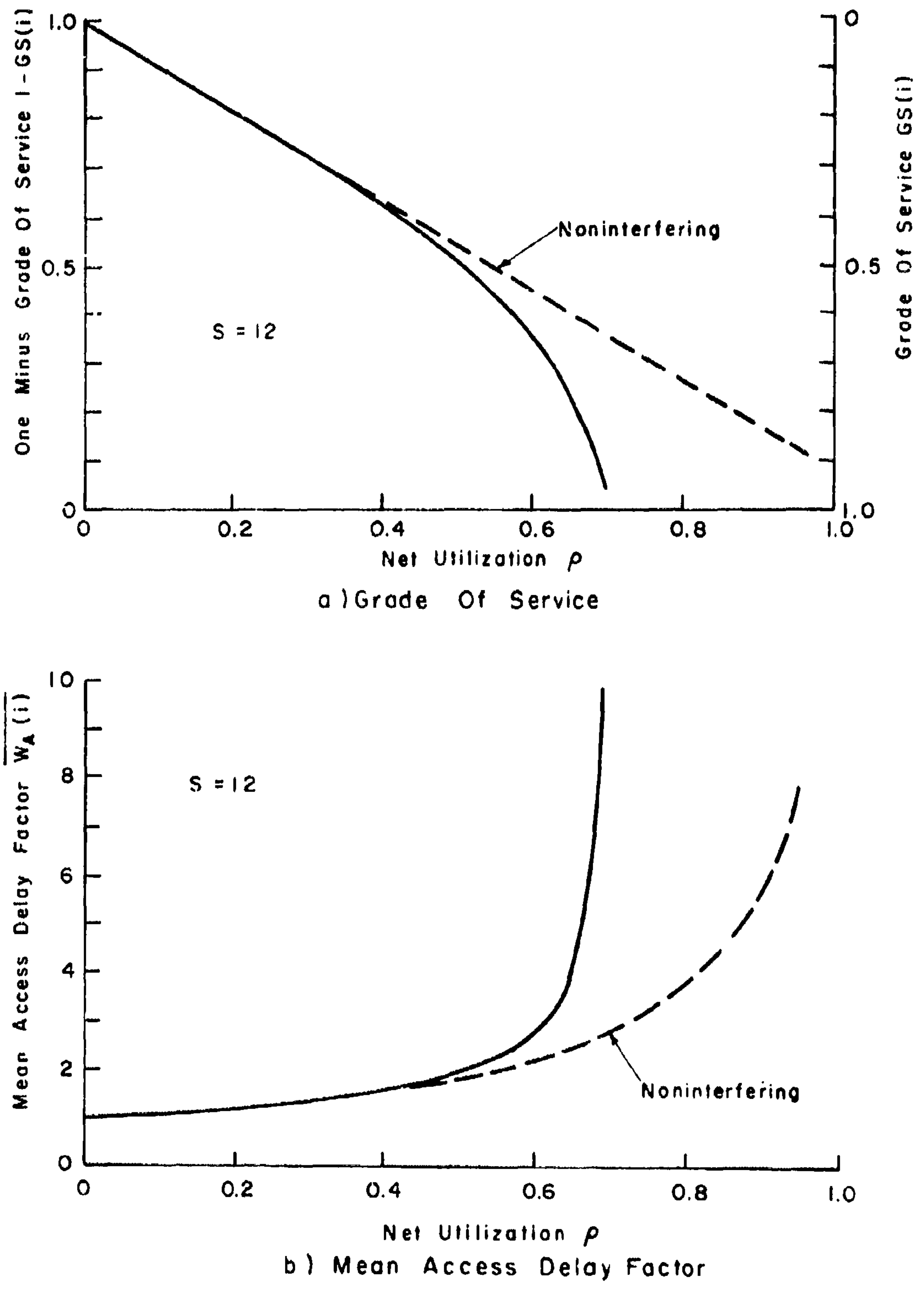
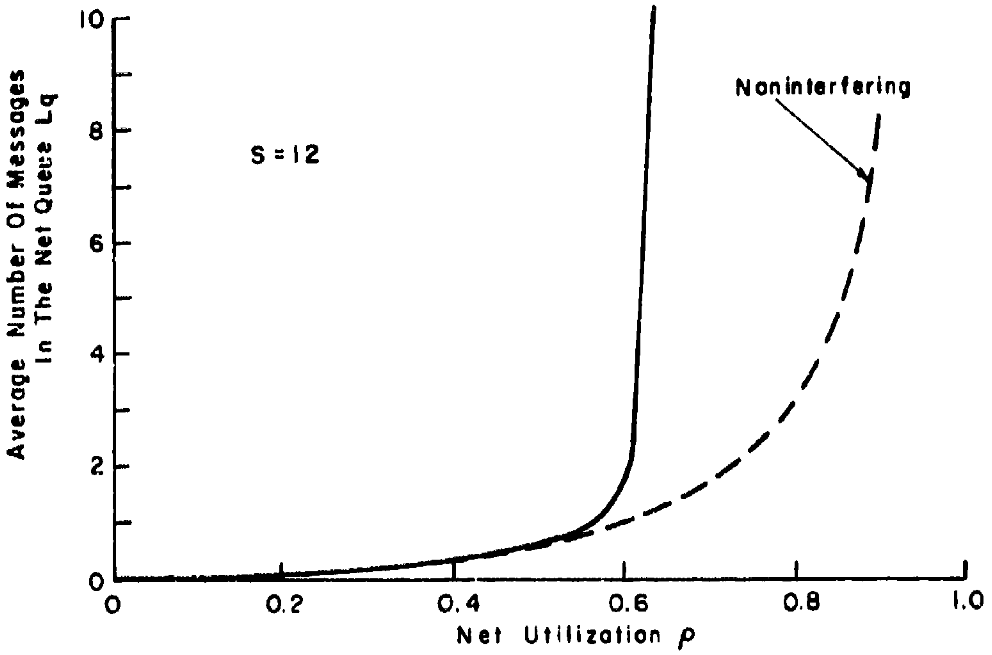
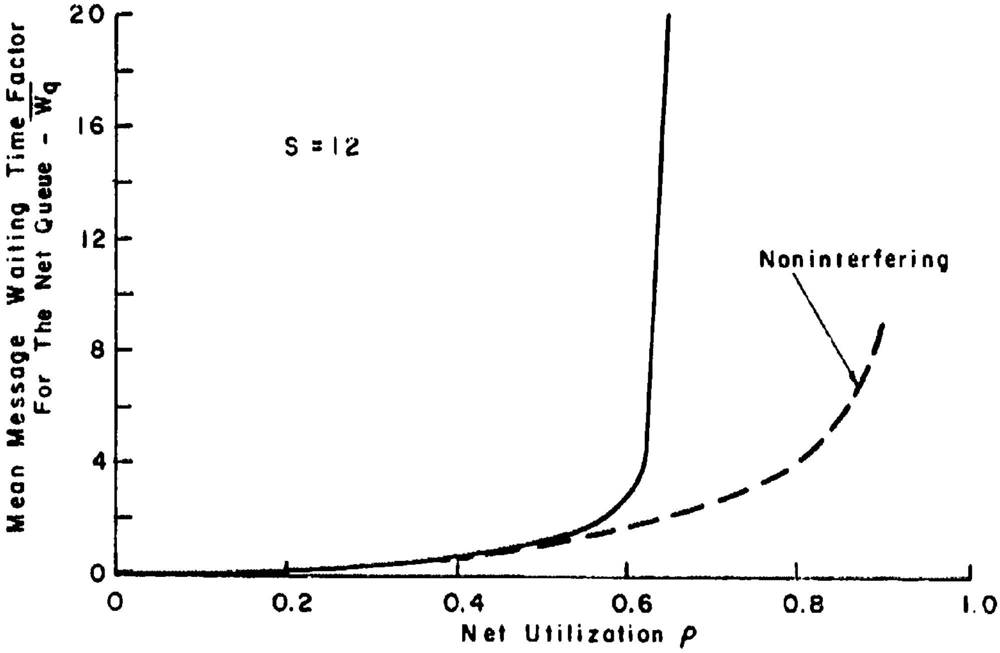


Fig. 3.1 OPERATOR ACCESS-SIGNALING INTERFERENCE



a) Net Queue Length



b) Net Queue Waiting Time Factor

Fig. 3.2 NET PERFORMANCE - SIGNALING INTERFERENCE

- A net employing asynchronous signaling cannot have a utilization greater than 0.65 without severe performance degradation. It is important to note that as a result of physical constraints a net with voice signaling is asynchronous.

- For utilizations less than 0.4 the difference between svnchronous and asynchronous signaling is not significant. This would indicate that for other results (e.g., MADA) the question of signaling synchronization is not important as long as the utilization is low enough.

- The results are based on a linear model. It is possible that net breakdown (zero information flow) which is a nonlinear event could occur in high utilization conditions due to operator confusion. It would appear desirable then in a net with asynchronous signaling to keep the utilization well below the knee of the curve.

- The mutual interference problem should be extended to the MADA system to evaluate its utilization limits. It is possible because of the multiple frequencies that they could be much higher. This is a consequence of the probability that all frequencies in a MADA system are busy being lower than the probability that the single frequency in a dedicated net is busy. It is therefore less likely that mutual signaling interference will occur.

4. COMPARISON OF DEDICATED NETS AND MADA

4.1 Introduction

Although changes in net performance when converting from voice to digital signaling are important as are the effects of various signaling features such as preempt, of more significance is the performance change resulting from a conversion from discrete nets to a multiple accesss - discrete address (MADA) system where several nets have access to several frequencies. There are a number of reasons for the significance of MADA. First of all both theoretical[1] and experimental[3] analysis indicates that conversion from voice to digital signaling will result in small improvements in performance in nets where the utilization is low to moderate. A significant number of nets fall into that category. With MADA there is more to be gained than net performance. A frequency spectrum savings could be realized because of the net grouping philosophy of the MADA system.

A second reason for the importance of analyzing a MADA system is logistics. Digital signaling can be introduced to a single net at a time and also tested in that way; MADA must be introduced to a number of nets and testing must be done on a larger scale. Because of this a greater dollar investment is required and it adds more importance to having a reasonable idea ahead of time of what performance to expect from a MADA system.

The purpose of this section of the report is to examine the effects on net performance and frequency spectrum utilization when converting from discrete nets to a MADA system. To make the results more relevant, a MADA system suggested by Feeney and Beitscher[4] of the Naval Electronics Laboratory Center has been modeled.

4.2 Scope of Application

A queueing discipline for a single frequency net had previously been[1] structured. To compare the performance of the single frequency net to a MADA system a queueing discipline for the MADA system was structured. The MADA system is illustrated in Fig. 4.1. The block diagram of Fig. 4.1 represents the equipment which would be located on each ship that had stations which formed the MADA system.

On each ship in the MADA system the stations belonging to the MADA system would each have a MADA signaler. These signalers would be connected through the remote phone units and various patch panels to an automatic switch panel. Connection of the various operators to the RF equipments is made through the automatic switch panel and controlled by the channel selection control. In addition to specifying a hardware configuration for the MADA system, a number of assumptions have been made relative to its operation. They are:

- Each ship belonging to the MADA system has symmetric frequency access; that is, each ship has the same number and the same frequencies as any other ship in the MADA system.
- The channel selection control has a monitor and memory capability. This capability allows the channel selection control to monitor and store which frequencies are busy and what stations are using them.
- If an operator attempts to call a station that is busy when one or more frequencies are not busy, he will receive a busy station indication from the channel selection control and no time on the frequency will be required.

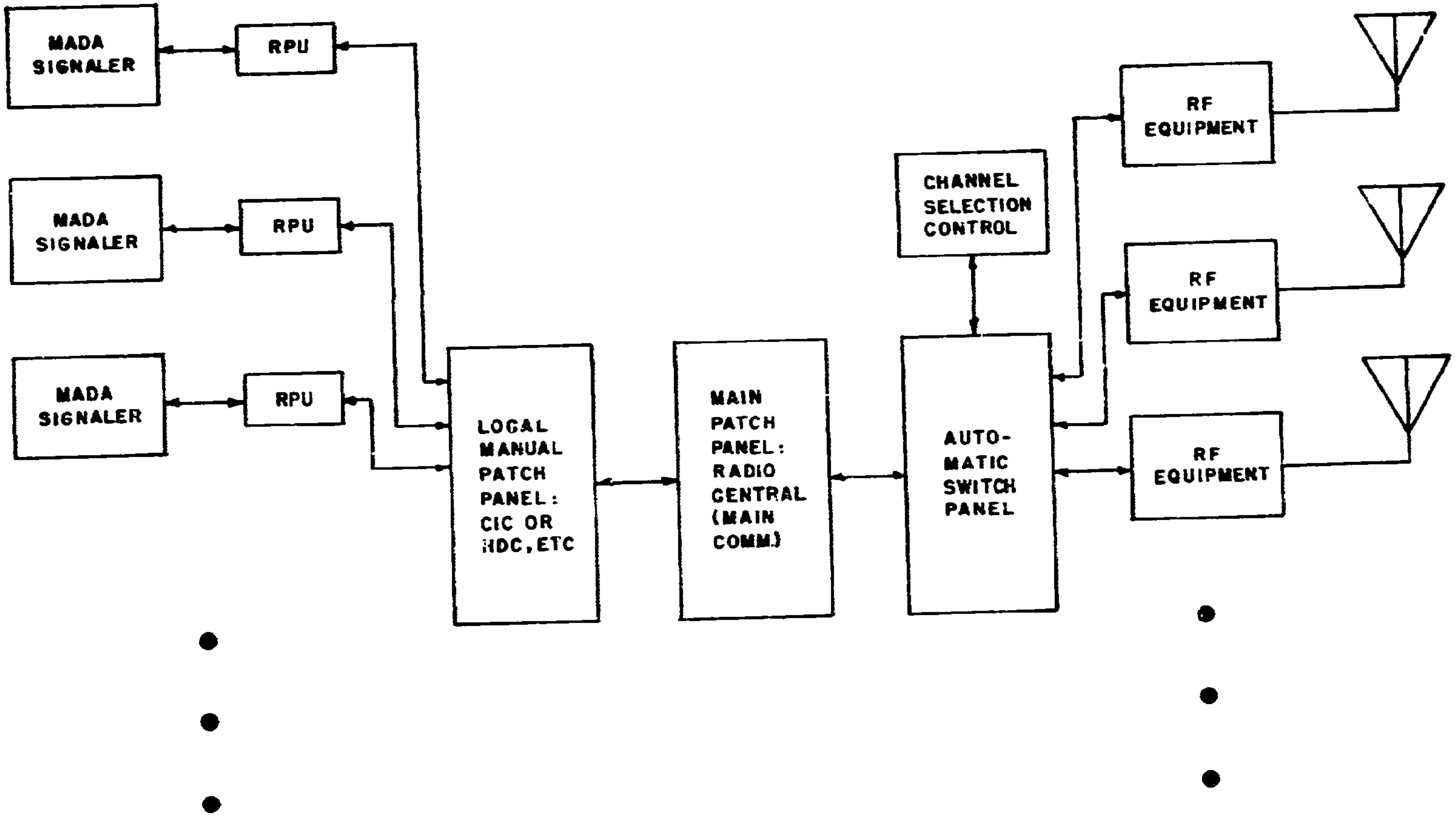


Fig. 4.1 MADA SYSTEM

- The processing time required by the channel selection control is negligible in comparison to the message and signaling times.

For the queueing discipline as presently structured the scope of the MADA system is limited to systems composed of from two to seven nets utilizing from two to five frequencies. Each net in the system has a message generation rate $\lambda(i)_n$ and $S(i)$ stations. The $\lambda(i)_n$ and $S(i)$ may be different for each net; however, the message generation rate $\lambda(i)$ for each station of a particular net is assumed the same and equal to

$$\lambda(i) = \lambda(i)_n/S(i) \tag{4.1}$$

The average message length for each of the stations in all of the nets is assumed to be the same and is equal to μ^{-1} Further, there is no message traffic between stations in separate nets. The message generation statistics are Poisson and the message lengths have an exponential distribution.

The number of stations in a particular net can vary from three to an arbitrarily large number. The only restriction on the values of $\lambda(i)_n$ and μ is

$$\sum_{i=1}^{T} \frac{\lambda(i)_n}{\mu} = \sum_{i=1}^{T} \rho(i)_n = \rho_s < k \tag{4.2}$$

where T is the number of nets in the MADA system, $\rho(i)_n$ is the utilization of net i, ρ_s is the utilization for the system and k is the number of frequencies used by the MADA system.

4.3 Description of Results

To determine the effects on performance of a MADA system, a task group which has five dedicated nets that are physically compatible with MADA is assumed. To simplify the situation somewhat, each net is assumed to have the same number of stations ($S(i)_n = S = 12$) and the same message generation rate. The

average message length is assumed to be equal to 20 seconds. Without MADA each of the five nets has one frequency. With MADA the five nets are grouped together with all five frequencies available.

To evaluate the effects of MADA four performance measures are used. They are the Grade of Service, the Mean Access Delay, the Expected Number of Messages in a Net Queue and the Mean Message Waiting Time in the Net Queue. Interpretation of these performance measures is not quite the same with and without MADA. Without MADA the Grade of Service is the probability that the frequency is busy when an operator wishes to call. With MADA is also included the probability that a called station is busy when a frequency is available. The Mean Access Delay is based on the respective delays encountered in each of the two configurations. Expected net queue lengths and message waiting times are identical in interpretation for both configurations since a message is considered in queue regardless of whether it is delayed by a busy frequency or a busy station.

The four performance measures are illustrated in Figs. 4.2 and 4.3 for one of the nets as a function of net utilization.* The Mean Access Delay and Net Queue Waiting Time have been plotted with μ normalized to one. From the curves the following observations are made:

- There is a significant improvement in the Grade of Service for 70 percent of the range of net utilization.
- The available utilization for a specified level of net performance is increased by more than 25 percent up to a utilization of 0.6 for the dedicated net. This means that with MADA a net could either

*The parameter ρ, used as the abscissa for the dedicated net, is equivalent to $\rho(i)_n$ for the MADA system.

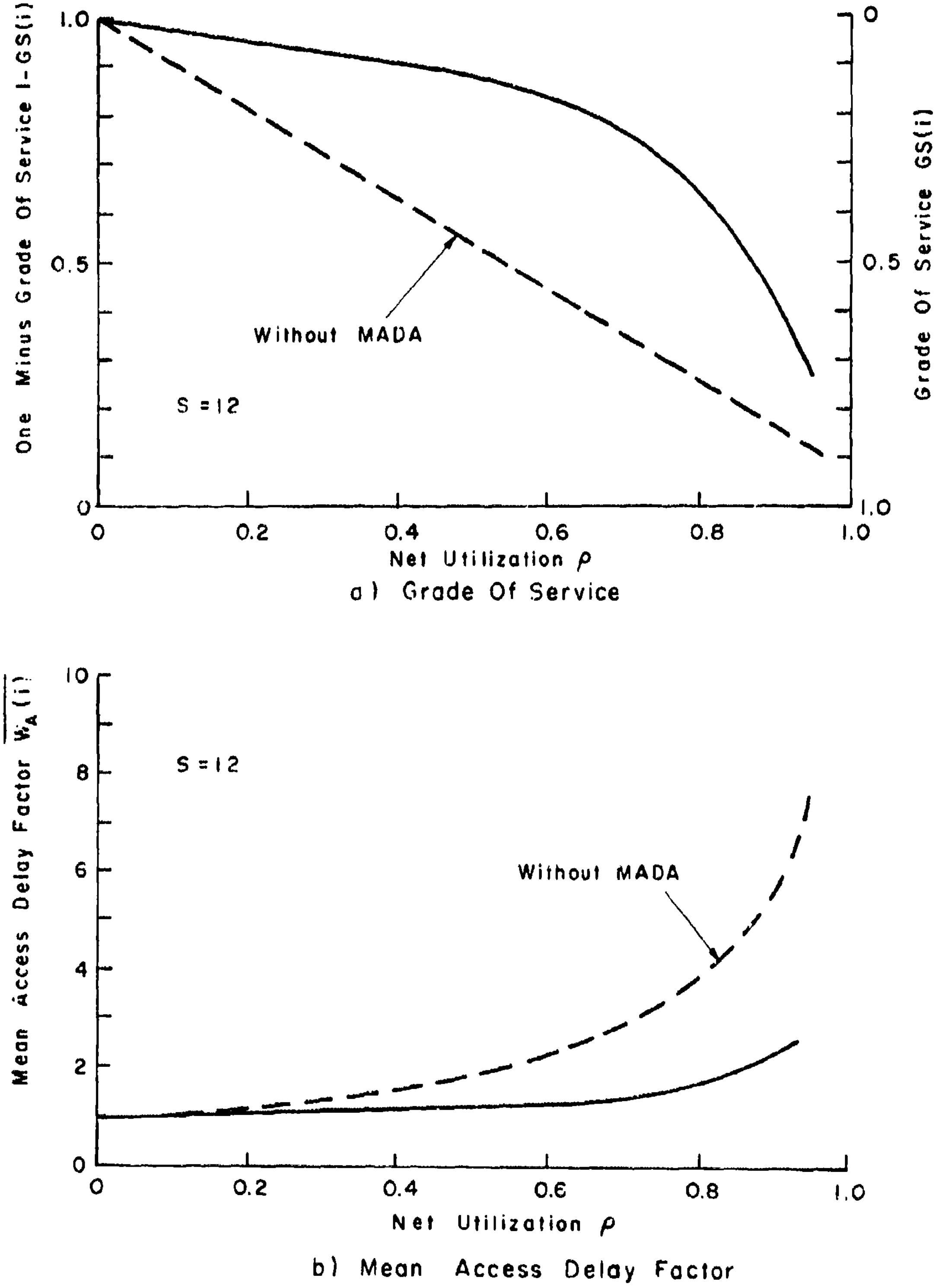
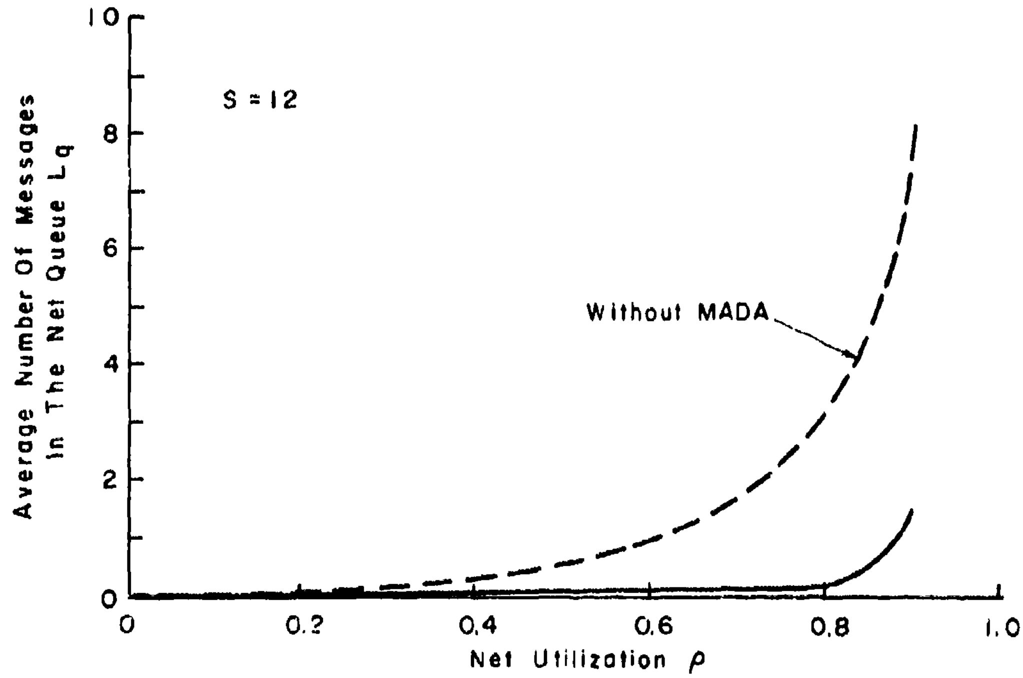
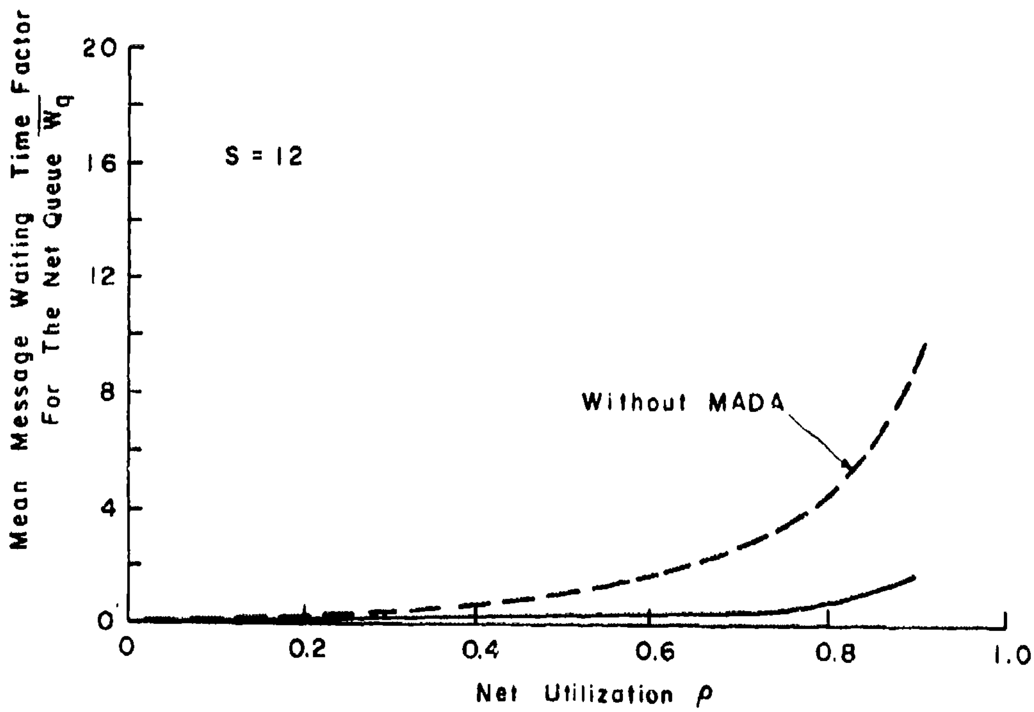


Fig. 4.2 OPERATOR ACCESS - MADA



a) Net Queue Length



b) Net Queue Waiting Time Factor

Fig. 4.3 NET PERFORMANCE - MADA

handle larger amounts of traffic with no performance change or handle the same traffic with improved performance.

- The improvement in Grade of Service below $\rho = 0.5$ indicates that it is likely that a frequency spectrum savings can be realized.

4.4 Frequency Spectrum Savings with MADA

The example illustrated in Figs. 4.2 and 4.3 assumed a one to one conversion to MADA with no reduction in the number of total frequencies. If the total utilization for the system is low enough, then it is possible to reduce the number of frequencies without degrading the individual net performance. In Eq. (4.2) it was pointed out that the total system utilization ρ_s should be less than the number of frequencies k. Therefore the number of frequencies can be reduced as long as k is greater than ρ_s. However as the limit of net utilization is approached (i.e., $\rho_s \rightarrow k$) there will be a sharp degradation in net performance. To insure that net performance is not degraded when converting to a MADA system with fewer total frequencies, ρ_s should be kept less than 75 percent* of k.

Assume that each of the five nets in the previous example has a utilization less than 0.4

$$\rho(i)_n < 0.4 \tag{4.3}$$

The total net utilization would then be

$$\rho_s = \sum_{i=1}^{5} \rho(i)_n < 2.0 \tag{4.4}$$

*This number is based solely on the examples used (Table 4.1) and may require slight changes for different net groupings.

Utilizing the 75 percent criterion stated previously, the MADA system should not degrade performance with three frequencies. This would represent a savings of two frequencies. To demonstrate this the performance measures are listed in Table 4.1 for the discrete net and the three frequency MADA net with $\rho(i)_n$ less than 0.4. It is clear from the table that no aspect of net performance considered has been degraded.

Table 4.1

Three Frequency MADA Example

Performance Measure	$\rho(i)_n$	Dedicated Net	MADA Net
GS(i)	0.2	0.183	0.075
	0.4	0.367	0.312
$\overline{W_A(i)}$	0.2	1.225	1.080
	0.4	1.579	1.454
L_q	0.2	0.050	0.002
	0.4	0.267	0.020
$\overline{W}_q$	0.2	0.250	0.092
	0.4	0.668	0.505

4.5 Conclusions

From the numerical results it is possible to draw a number of conclusions concerning MADA. They are as follows:

- Conversion of a dedicated net system to a MADA system results in performance improvements. The improvement with MADA can be explained in terms of the busy frequency as follows: The probability of five frequencies in five independent nets all being busy is less than the probability of one being busy. Therefore when nets have access to all frequencies it would be suspected intuitively that there would be an improvement.

- Conversion to a MADA system will generally permit frequency spectrum savings. The amount of spectrum savings would depend on the number of dedicated nets combined and the performance levels required.

- Any frequencies saved in conversion to MADA presents an alternative to preempt. The extra frequency or frequencies could be used for high priority (preempt) messages. The performance would probably be comparable to a preemptive system. In addition no special signaling equipment would be required for the preempt.

- The mutual interference problem will probably not restrict the available utilization with MADA as severely as in the dedicated net. This is based upon the idea that all of the frequencies used by the MADA system are seldom busy. In any event this concept should be considered quantitatively.

5. EFFECTS OF BUSY SIGNAL AND HOLD CALL

5.1 Introduction

Two signaling features which are quite closely related are hold call and busy signal. This simularity exists in both the net environment and in the queueing discipline. Because of this they are considered jointly.

The busy signal and hold call alternatives are only of significance in nets having access to two or more frequencies or MADA systems with two or more frequencies. Busy signal in a voice net occurs when one operator attempts to call another operator who is busy on a different frequency. The importance of busy signal is attributed to the frequency utilization involved in the call-up attempt and busy response. The same problem exists with digital signaling; however, it can be removed by furnishing the signaling equipment with monitor and memory capabilities. With these capabilities a signaler could store the identity of busy stations and there would be no need for frequency utilization. Busy signal becomes more important here since there is a trade-off between equipment complexity and frequency utilization.

Hold call in a voice signaling net does not seem to make physical sense. Therefore hold call is considered only in the context of nets or MADA systems having digital signaling. Use of hold call occurs when an operator determines that the operator he is attempting to call is busy. The calling operator then signals the called operator to call him back when he is finished with the current transmission. The purpose of hold call is operator convenience. An important question to be answered concerns the amount of convenience obtained for the price of frequency utilization, equipment complexity, and the system degradation due to the extra frequency utilization.

5.2 Scope of Application

A queueing discipline was structured which encompassed both busy signal and the hold call signaling features. The signaling method may be voice or digital for the busy signal and is digital for the hold call. The queueing discipline covers one to seven nets having from two to five frequencies. When a single net is considered each of the S stations in the net may have a different message generation rate $\lambda(i)$ and S may vary from three to an arbitrarily large number. If the nets are grouped into a MADA system then each of the T nets can have different message generation rates $\lambda(i)_n$ and numbers of stations $S(i)$. The message generation rates for each of the stations in a particular net is the same. In all cases the average message length is μ^{-1}. Also, the average time on the frequency required for a busy signal or hold call is $(\rho\mu)^{-1}$ where ρ is generally larger than one. Messages are assumed generated by a Poisson process and message lengths are assumed exponentially distributed.

In a net or MADA system which has digital signaling, the busy signal is assumed to be an automatic function. When an operator attempts to call an operator who is busy on another frequency, the busy operator's signaler responds with a busy signal and the busy operator is not interrupted. If hold call were available the busy operator would be alerted to the call and also be informed of who was calling. When his present call was finished he would return the call. In a net with voice signaling it is assumed that the operator would monitor aurally the frequencies. This would restrict the number of frequencies to two or three. It is also assumed that the operator would have some self actuated electronic device for signaling his busy condition. This would eliminate a need for him to interrupt his present transmission.

5.3 Description of Results - Busy

To determine if the added frequency utilization resulting from busy signal is significant enough to warrant a signaling system that has a monitor and store capability, a two frequency net with digital signaling is evaluated with and without busy signal. The net is assumed to have 20 stations; each has the same message generation rate. An average message length is assumed to be 20 seconds and the average time to transmit the call-up and the busy signal is assumed to be 1 second.

Four performance measures are used to evaluate the effect of busy signal. They are the Grade of Service, Mean Access Delay, Expected Number of Messages in the Net Queue and the Mean Message Waiting Time in the Net Queue. It is important to note that even though the frequency is accessed when a busy signal is encountered, that event is still considered as a delay; therefore, it contributes to all of the performance measures (e.g., a message is considered in queue during a busy signal).

The performance measures are listed in Table 5.1 for three values of net utilization with and without* busy signal. It is clear from the table that for the example there is very little change in performance.

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*Monitor and store is assumed.

Table 5.1

Performance With Busy Signal

Performance Measure	i	Without Busy	With Busy
GS(i)	0.6	0.128	0.128
	1.2	0.357	0.363
	1.8	0.728	0.729
$\overline{W_A(i)}$	0.6	1.149	1.149
	1.2	1.555	1.564
	1.8	3.680	3.690
L_q	0.6	1.149	1.149
	1.2	1.555	1.564
	1.8	3.680	3.690
$\overline{W_q}$	0.6	0.176	0.176
	1.2	0.676	0.683
	1.8	4.245	4.248

To consider the effects of busy signal in a voice signaling net having two frequencies, it is necessary only to adjust the average message length and the average time to transmit call-up and busy signal. They are assumed to be 25 seconds and 5 seconds respectively. As with the digital signaling there is very little change in performance.

5.4 Description of Results - Hold Call

To illustrate the effect of hold call a two frequency net with digital signaling is evaluated with and without hold call. The net is assumed to have 20 stations with the same message generation rate. The average message length is assumed to be 20 seconds and the average time to transmit the hold call is 1 second. It was also assumed that given the opportunity an operator would use hold call 10 percent of the time.

Again four performance measures are used. They are the Grade of Service, Mean Access Delay, Expected Number of Messages in the Net Queue and the Mean Message Waiting Time in the Net Queue. Unlike with busy signal an operator transmitting a call-up, receiving a busy and then transmitting a hold call is <u>not</u> considered delayed. However his message is still considered in queue even though it will be initiated by a different operator. The performance measures are listed in Table 5.2 with and without hold call. Three values of net utilization are considered. As was the case with busy signal there appears to be very little change in performance. These results are discussed in the conclusions.

Table 5.2

Performance With Hold Call

Performance Measure	ρ	Without Hold Call	With Hold Call
GS(i)	0.6	0.128	0.128
	1.2	0.357	0.356
	1.8	0.728	0.728
$\overline{W_A(i)}$	0.6	1.149	1.149
	1.2	1.555	1.555
	1.8	3.680	3.680
L_q	0.6	0.106	0.106
	1.2	0.811	0.812
	1.8	7.641	7.642
$\overline{W_q}$	0.6	0.176	0.176
	1.2	0.676	0.677
	1.8	4.245	4.245

5.5 Conclusions

From the numerical results and physical considerations it is possible to draw a number of conclusions concerning busy signal and hold call. They are as follows:

- It appears that in nets or MADA systems having digital signaling, there is little difference between a busy signal in which the frequency is utilized and a monitor and store signaler which would provide a busy indication with no frequency utilization. This is dependent upon the call-up/busy signal air time being small compared to average message length (e.g., $\beta > 10$).
- The previous[1] results for voice signaling nets having more than one frequency are good approximations even though busy signal was not included. This assumes that an operator who is busy can respond to a call without interrupting his call (e.g., self actuated electronic busy signal).
- Hold call appears to provide little change in performance or operator convenience ($GS(i)$ and $W_A(i)$). This is intuitively attributed to two factors. First, for each message an operator puts in hold he also receives one from someone else. The net gain would appear to be zero. Second, at low utilization hold call is seldom required while at high utilization an operator is more likely to find busy frequencies than a busy station.

6. PREEMPTIVE AND NON-PREEMPTIVE PRIORITY

6.1 Introduction

In many tactical radio nets there is often a need to send one message before another. This introduces message priorities. Also if the message is of sufficient urgency it may be necessary to break in on a current transmission. This introduces preemptive message priorities.

In a previous report[1] the problems of preemptive and non-preemptive priority were addressed. However at that time the operator performance measures, Grade of Service and Mean Access Delay, were not considered. In addition an assumption was made for the preemptive case which is not realistic. Specifically, it was assumed that any message that was preempted would be continued from the point of preemption with no additional transmission time required. It should be clear that additional transmission time will always be required to re-establish (call-up) the preempted call. Also it is quite likely that some additional information will be required to set the context of the message. This will require added transmission time.

This section of the report has two objectives; first, to incorporate the operator performances measures into the queueing discipline and second, to consider the effects of the added transmission time required to send a preempted message.

6.2 Scope of Application

A queueing discipline has been structured for nets and MADA systems having preemptive or non-preemptive priority messages. Two levels of priority have been assumed. The queueing discipline can be applied to single nets having from one to five frequencies and MADA systems having from two to five frequencies. Thus far exact numerical solutions have only been obtained for three frequencies or less with approximate results for the four and five frequency cases. It appears

possible to obtain exact results for the latter two cases.

The solutions apply to nets having S stations (S = 3, 4, 5,...) where each station can have a different generation rate $\lambda(i)$. For MADA systems in which T nets (T = 2, 3,..7) are grouped, each net can have a different number of stations S(i) and message generation rate $\lambda(i)_n$. The stations of a particular net are all assumed to have the same message generation rate. The average message length for each station is assumed to be the same and the fraction of priority messages generated at each station is assumed the same and equal to r. Also Poisson message generation and an exponential message length distribution are assumed.

Because a two level priority system has been assumed the terminology can be simplified. The two message classes of the non-preemptive priority system will be referred to as priority and non-priority. For the preemptive priority system they will be referred to as preempt and non-preempt.

To completely specify the queueing discipline certain characteristics of the systems which are determined by physical implementation must be specified. They are as follows:

- A priority message cannot interrupt any message which is in transmission.
- When a transmission ends or a frequency is available an operator with a priority message is assured the frequency only if all other operators desiring the frequency have non-priority messages. If a mixture of operators with priority and non-priority messages require the frequency, an operator with a priority message will gain access to the frequency. The particular operator is selected randomly.

- A preempt message can interrupt a message in transmission only if it is a non-preempt message. Therefore, access to the frequency is certain only when the number of preempt messages in the net or MADA system is equal to or less than the number of assigned frequencies.

6.3 Description of Results

Two aspects of performance are important when considering preempt and priority messages; first, the performance of the operator when he has a preempt or priority message and second, the effect of having different message classes in terms of overall net performance. To examine these two aspects an example has been hypothesized. A single frequency net is considered that has twelve stations. For simplicity it is assumed that each station has the same message generation rate. It is also assumed that the average message length is 20 seconds and that 5 percent of all messages are priority or preempt depending on the system considered.

The nets having preempt or priority are compared to a reference net that has identical characteristics but does not have priority or preempt. To quantitatively evaluate performance four measures are used. They are the Grade of Service, Mean Access Delay, Expected Number of Messages in the Net Queue and the Mean Message Waiting Time in the Net Queue. The definitions for these measures apply in almost the same way with and without preempt or priority. The only difference is for the Grade of Service and Mean Access Delay. For these two measures separate results have been computed for priority and non-priority or preempt and non-preempt messages.

The results are illustrated in Figs. 6.1 and 6.2. Each of the four performance measures is plotted as a function of net utilization. The Mean Access Delay and the Net Queue Waiting Time have been plotted with μ normalized to one.

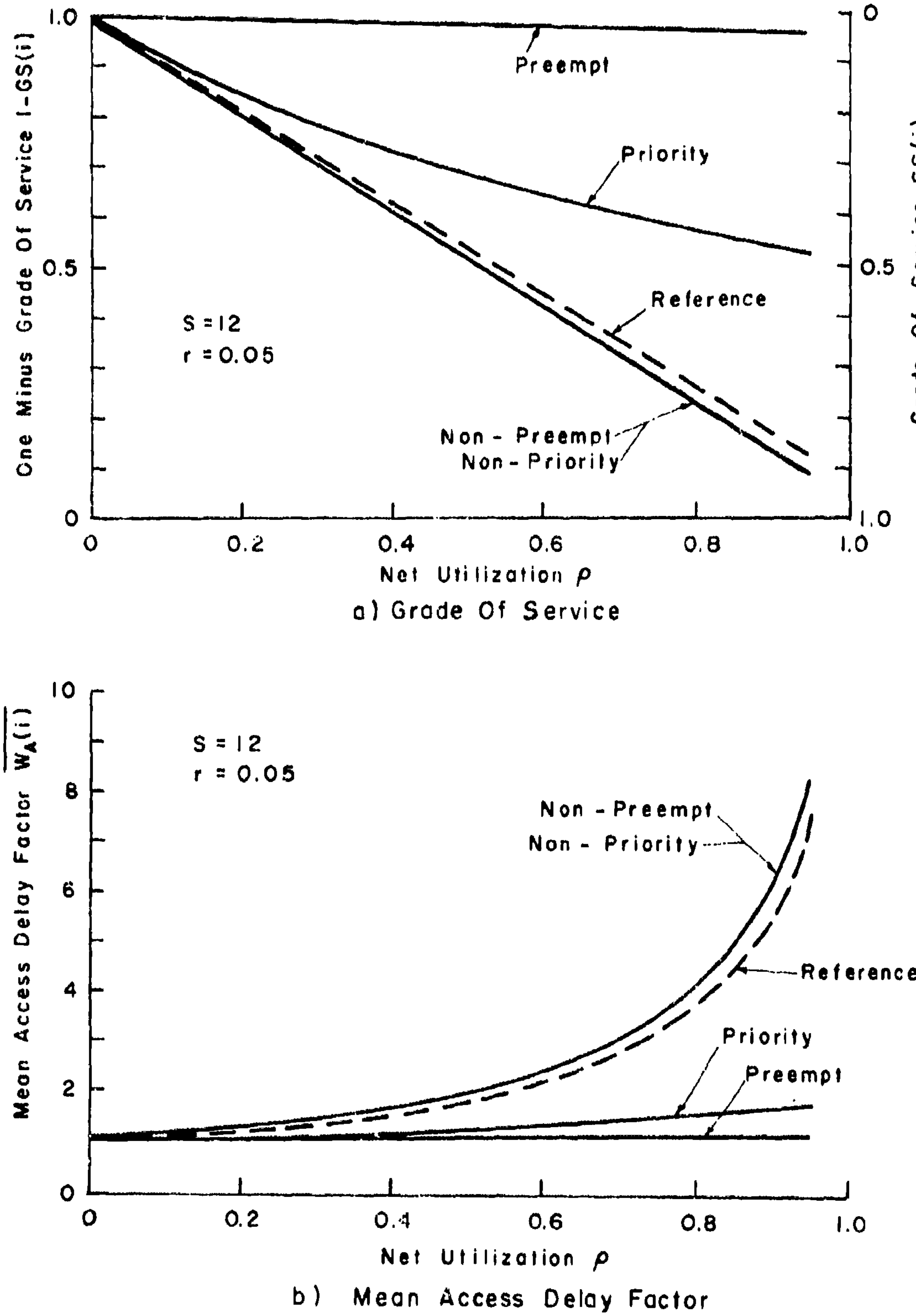


Fig. 6.1 OPERATOR ACCESS - PREEMPT/ PRIORITY

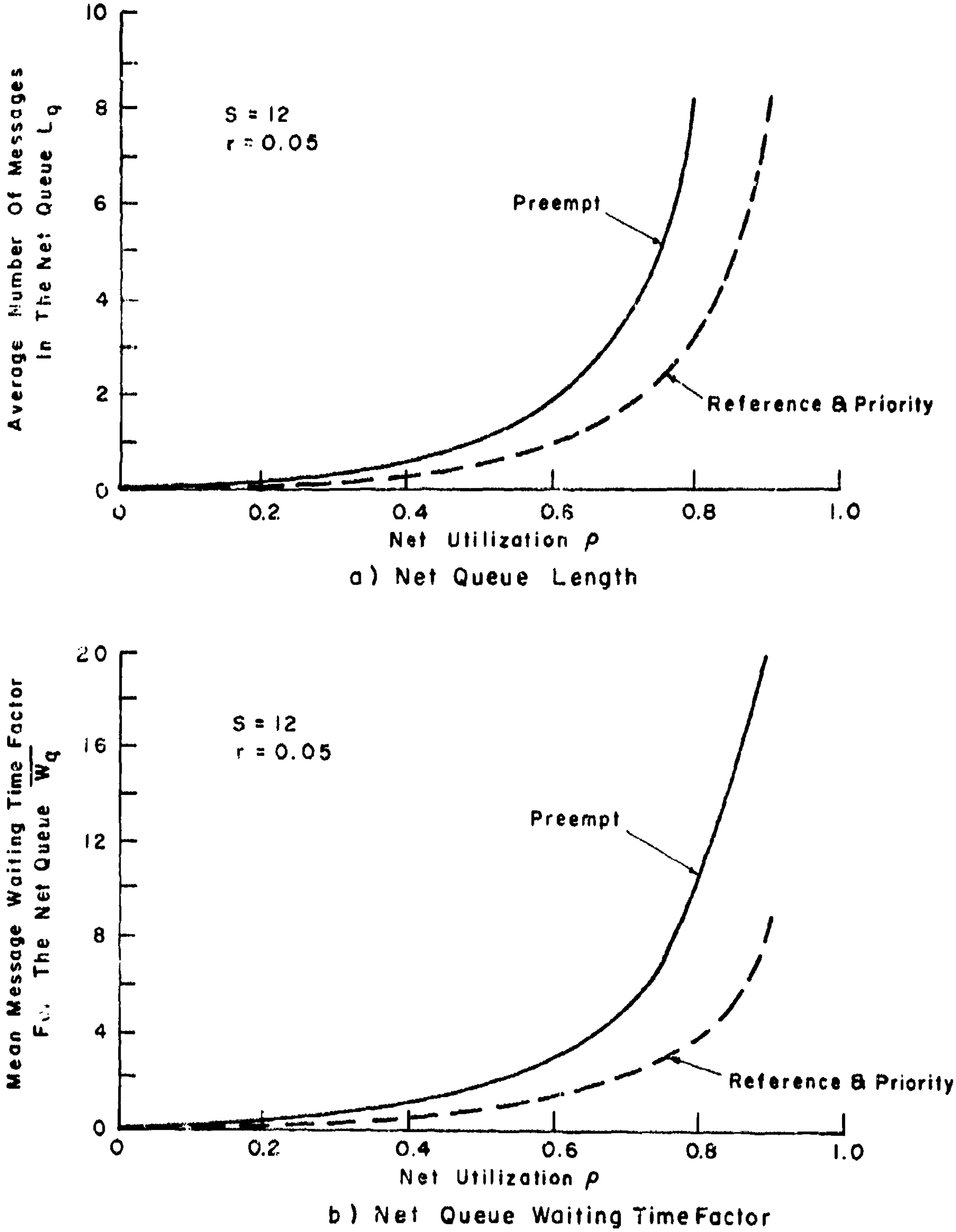


Fig. 6.2 NET PERFORMANCE - PREEMPT/PRIORITY

From the curves the following observations can be made:

- Operator access is significantly improved for preempt or priority messages for a large range of utilization; the improvement with preempt is greater.
- Operator access is changed very little for the non-preempt or non-priority messages.
- Net performance with priority signaling is unchanged; net performance with preemptive signaling is degraded (Fig. 6.2).

6.4 Conclusions

From the example and physical considerations it is possible to draw a number of conclusions. They are as follows:

- In a net with preemptive signaling the percentage of messages that are preemptive should be kept less than 5 percent. There are two reasons for this; first, the more preemptive messages there are the poorer the Grade of Service and second, somewhere between 5 and 15 percent preemptive messages (depending on net utilization), the net performance will break down completely. This is a result of non-preemptive messages being interrupted more than once.
- Use of preempt reduces the utilization which is available at a given performance level. This is a result of messages requiring retransmission.
- Improvements achieved with priority can also be achieved or exceeded by incorporating MADA. It is important to note that with MADA performance is

improved for all messages while with priority only a fraction of the messages experience a performance improvement.

- With MADA and priority or MADA and a separate frequency for priority messages, preemptive signaling may not be required. This would be significant since reliable preemption is difficult to achieve on a radio net. A study of this trade-off should be conducted.

7. NETS WITH MULTIPLE MEAN MESSAGE LENGTHS

7.1 Introduction

In the previous technical report[1] the problem of nets with messages having different mean lengths was addressed. Examples of such nets would be those having a mixture of discrete calls and net calls or nets where the message length was station dependent. Numerical results were previously obtained only for the nets having discrete calls and net calls and then only for the net performance measures. That work has been extended. Complete results are now available for the discrete call/net call problem and a queueing discipline has been developed for the station dependent message length. The purpose of this section of the report is to illustrate the discrete call/net call results.

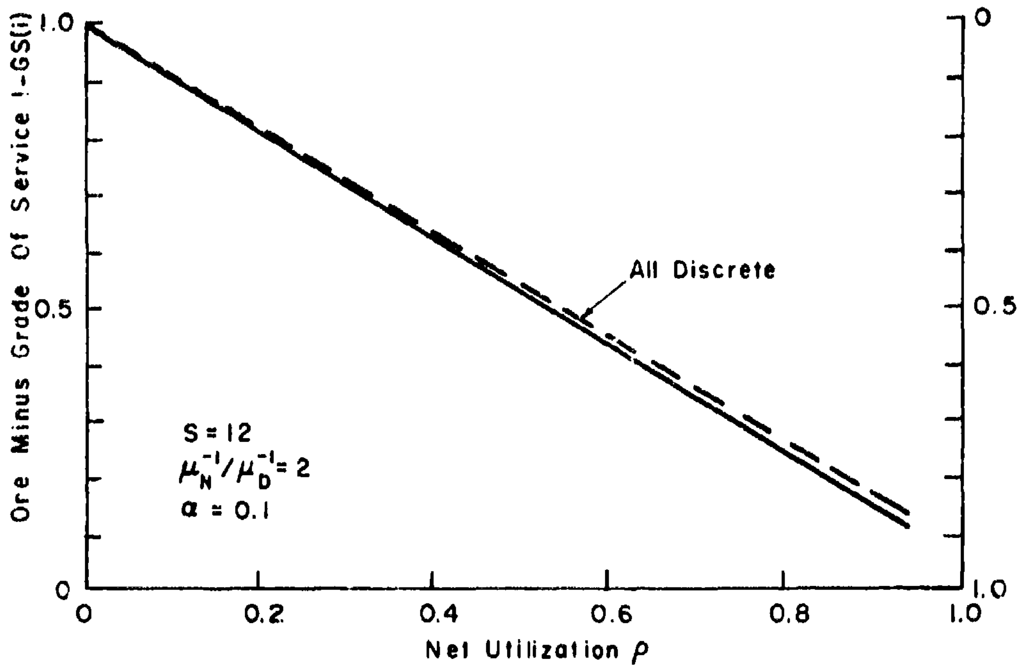
7.2 Scope of Application

The queueing discipline developed for the discrete call/net call problem applies to single frequency nets. The net may have S stations where S ranges from three to an arbitrarily large number. Each of the stations can have different message generation rates and two types of messages with different mean lengths. The proportion of the two types of message generated in each station is assumed to be the same. Nets utilizing voice or digital signaling are included. Poisson message generation and exponential message length distributions are assumed.

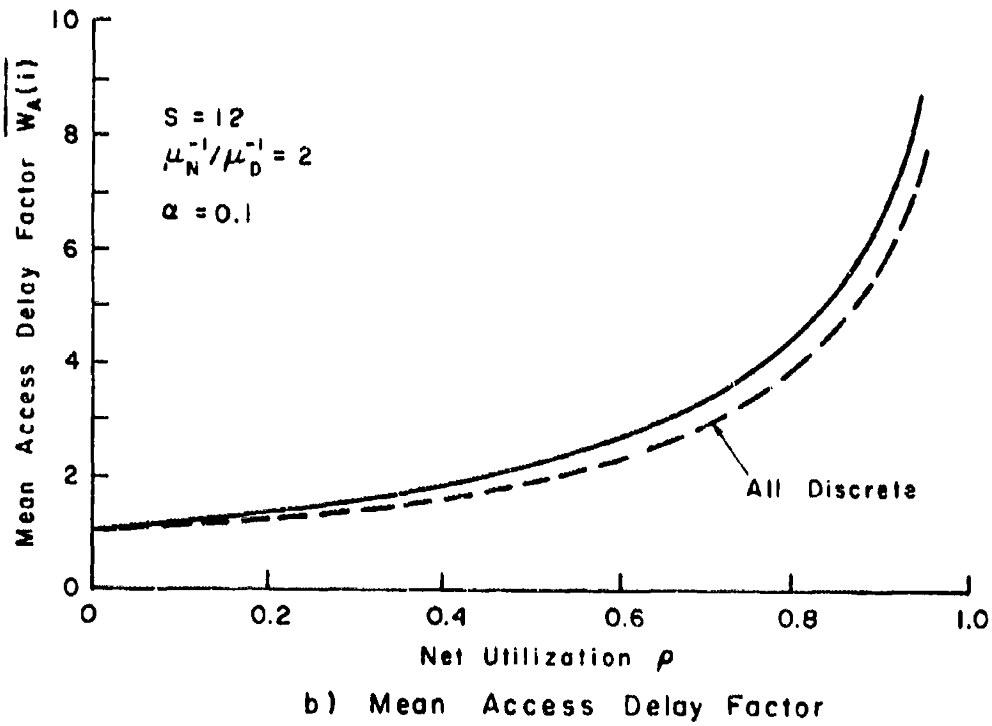
7.3 Description of Results

To illustrate the effect of net calls in a net, a comparison between a net with all discrete calls and a net with 90 percent discrete calls and 10 percent net calls ($\alpha = 0.1$) is assumed. Also it is assumed that the average length of the net calls is twice that of the discrete calls because of signaling. The net has twelve identical stations.

The four performance measures are illustrated in Figs. 7.1 and 7.2. Each of the performance measures is plotted as a function of net utilization. From the figures it can be observed that there is little difference in the two situations.



a) Grade Of Service



b) Mean Access Delay Factor

Fig. 7.1 OPERATOR ACCESS - NET CALLS

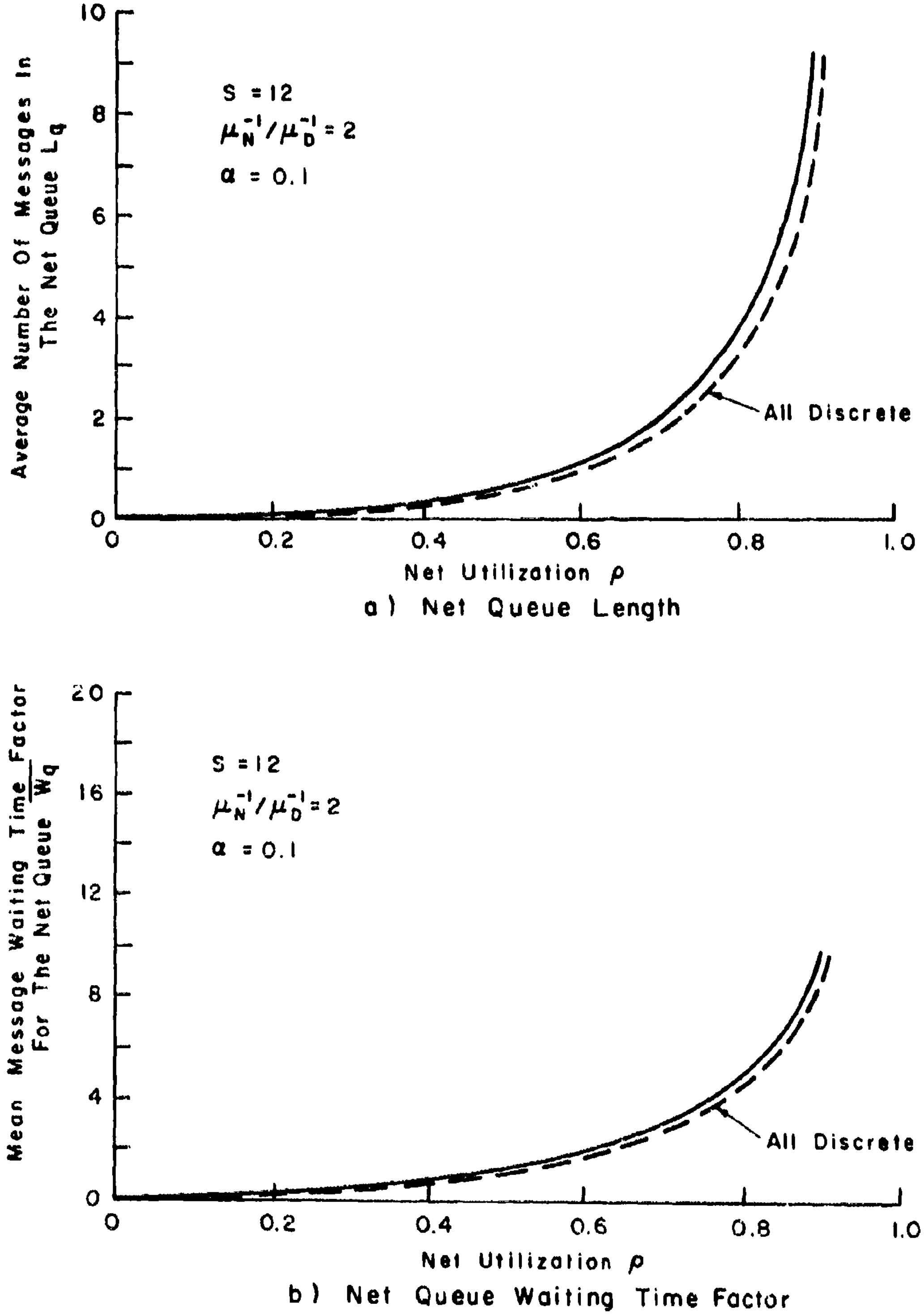


Fig. 7.2 NET PERFORMANCE - NET CALLS

8. NON-POISSON STATISTICS

8.1 Introduction

It was indicated in Section 2.2 of this report that the calling system - outer system model was not limited to Poisson statistics. It was stated that a large class of message generation and message length statistics could be used for the various queueing disciplines structured thus far. The most significant restriction is that of independent message generation.* This section of the report has been included to illustrate some results for Erlangian[5] message generation statistics; thus demonstrating the feasibility of using Non-Poisson statistics.

8.2 Scope of Application

The queueing disciplines which have been structured thus far can all be modified for Erlangian statistics. The only problem which might result would be that of obtaining numerical results and then only in the three, four and five frequency preemptive and non-preemptive priority situations. For the purpose of illustration the problem considered here was the single frequency dedicated net.

8.3 Description of Results

A twelve station single frequency net has been selected for illustration. It has been assumed that each of the stations has the same average message generation rate and that the average message length at each station is the same. Three separate Erlangian message generation distributions were used with $k = 2$, 3 and 4. The parameter k controls the variance of the Erlangian interarrival density function; as k increases the

*Removal of this restriction is currently under investigation.

variance becomes smaller. This is illustrated in Fig. 8.1 for k = 1, 4 and ∞ (k = 1 is the Poisson interarrival density function). It can be seen that for k = ∞ the variance is zero.

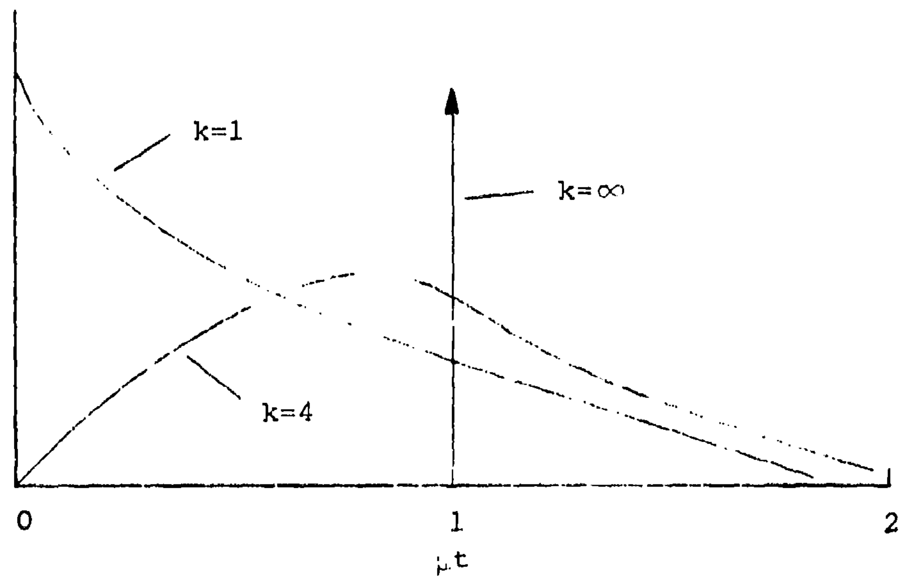
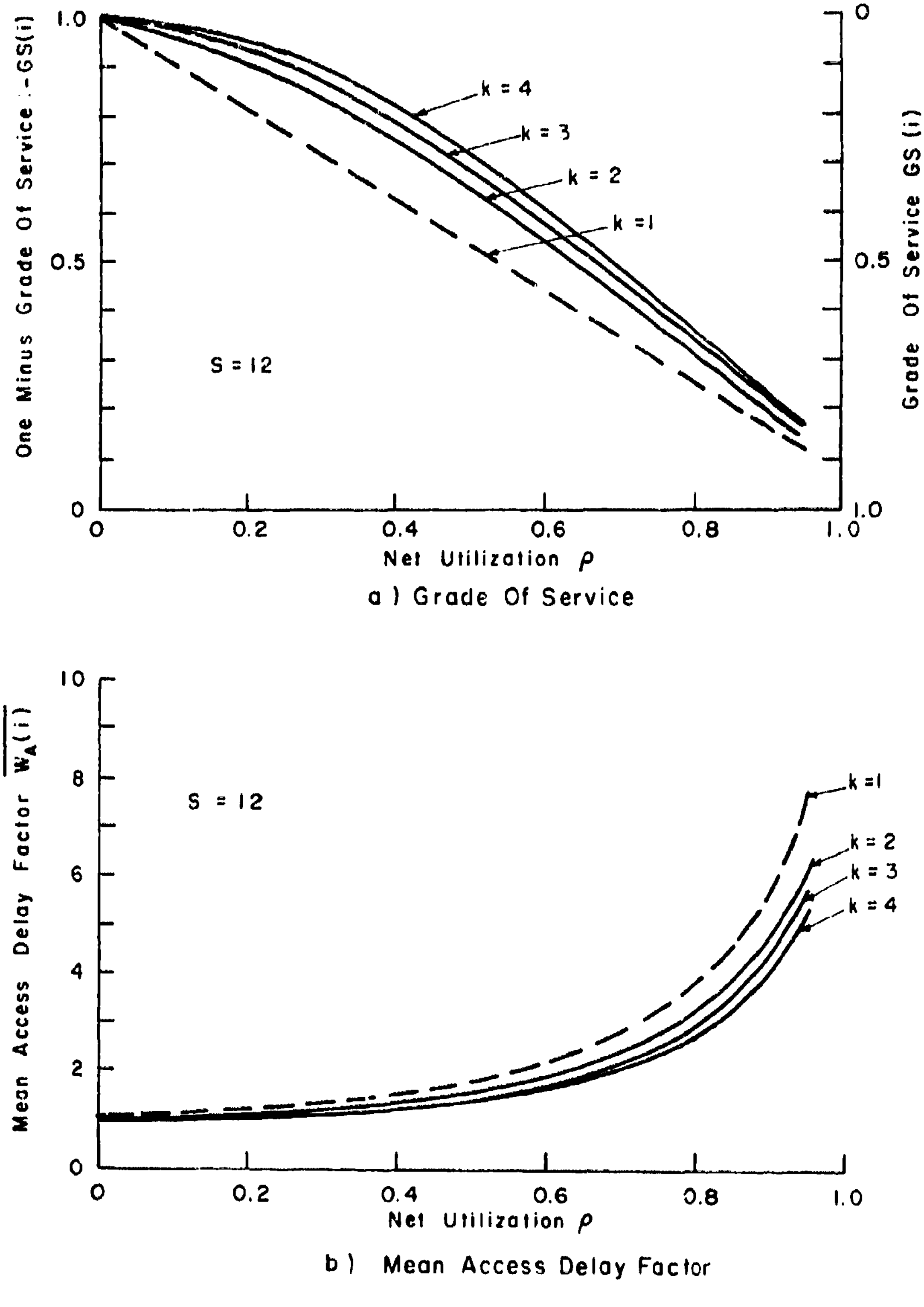


Fig. 8.1 Interarrival Density Functions

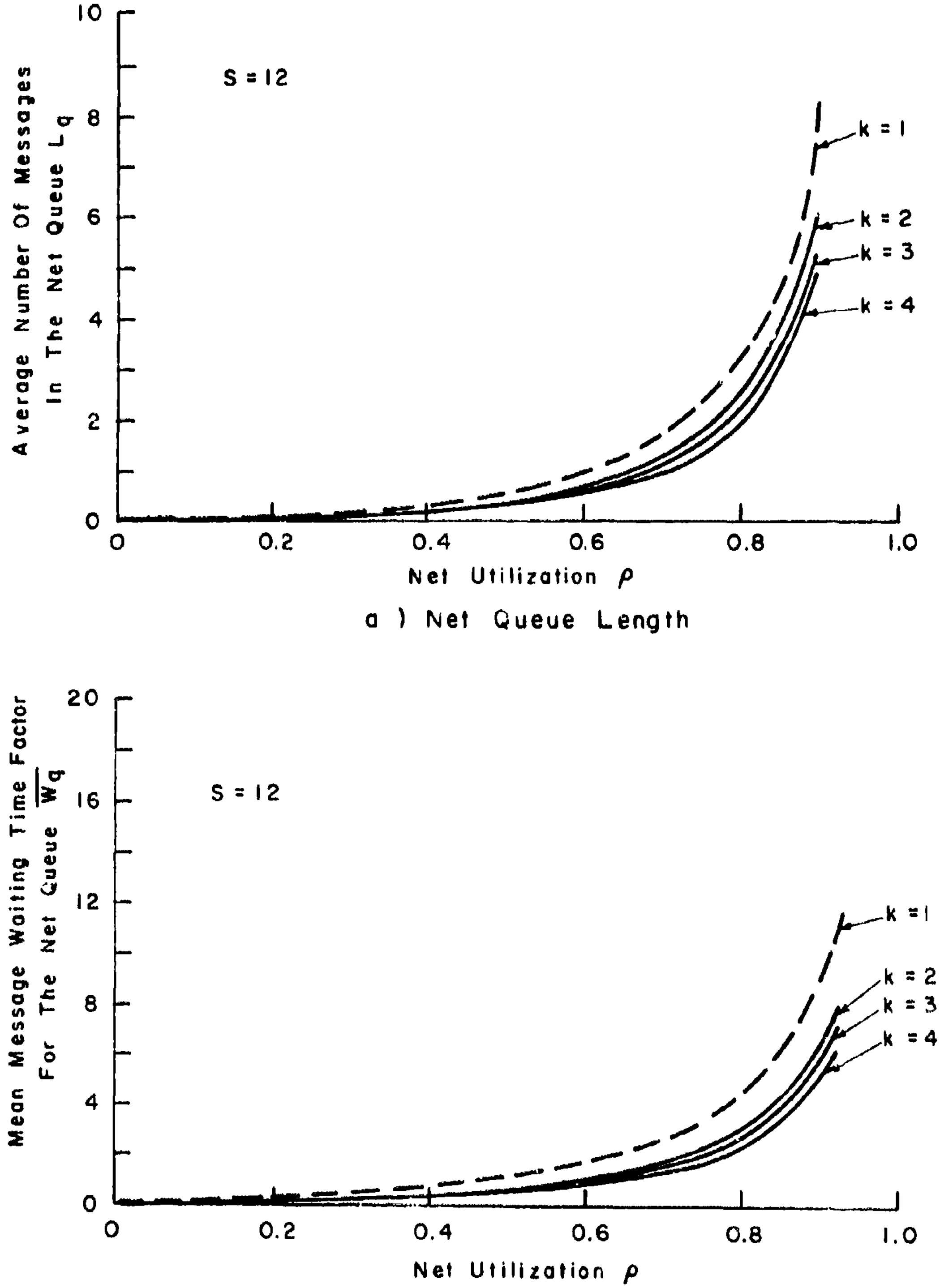
The four performance measures are illustrated in Figs. 8.2 and 8.3. Each of the performance measures is plotted as a function of net utilization. It can be observed from the figures that as k is increasing, performance is improving. This can be explained in terms of the variance of the interarrival density function. As the variance becomes smaller it is less probable that a large number of messages are generated in a short time interval; hence, there is less chance of a queue building up and overall performance improves. It is important to note the input statistics are a function only of the environment the net is in and that changing the net hardware or configuration does not change the message generation statistics. Therefore when comparisons between net configurations are made, the statistics should be the same in both cases.



a) Grade Of Service

b) Mean Access Delay Factor

Fig. 8.2 OPERATOR ACCESS - ERLANG INPUT



a) Net Queue Length

b) Net Queue Waiting Time Factor

Fig. 8.3 NET PERFORMANCE - ERLANG INPUT

9. REFERENCES

1. N. Thomopoulos, P. McManamon and R. Janc, Study of Concepts for Navy Communications (U), Technical Report, AD724340, Contract N00014-70-C-0375, May 1971

2. G. Reuter and W. Ledermann, On the Differential Equations for the Transition Probabilities of Markov Processes With Enumerably Many States, Proceedings of Cambridge Philosophical Society, Vol. 49, 1953

3. H. Beitscher and G. Dorsey, Evaluation of Twelve Bicircuit Digital Signalers (U), Letter Report B601 - Ser. 1200 - 176, Naval Electronics Laboratory Center, June 1971

4. H. Feeney and H. Beitscher, Amphibious Warfare Communications Systems Comparison and Proposed Development Plan (U), Technical Document 103, Naval Electronics Laboratory Center, November 1970

5. P. Morse, Queues, Inventories and Maintenance, John Wiley and Sons, 1958

GLOSSARY

1.	Net	Abbreviated form of tactical voice radio network and describes a group of communication stations with a common tactical operational function.
2.	Station	A physical location (surface, subsurface, air or ground) which contains one operator and has access to one or more transmitters and receivers.
3.	Operator	An individual whose function, from the analysis viewpoint, is to transmit and receive messages.
4.	Frequency	A simplex voice radio channel which can be in the HF, VHF or UHF bands.
5.	Primary frequency	Radio frequency used for communication under normal circumstances.
6.	Secondary frequency	Radio frequency or frequencies used for backup when the primary frequency is not available for use.
7.	Dedicated frequency	Radio frequency used exclusively by one net.
8.	Shared frequency	Radio frequency used by more than one net.
9.	Message time	The continuous time duration consisting of signaling, information transfer and pauses when information is transmitted from one station to another. (Syn. holding time)
10.	Transmission time	The message time that does not include the pauses.
11.	Signaling	The portion of the message (excluding pauses) which does not contain information. The functions included are ring-up, ring-back, ring-off, preempt, priority, busy and hold.

GLOSSARY (Continued)

12.	Voice signaling	Signaling implemented by voice transmission.
13.	Digital signaling	Signaling implemented by digitally coded tone transmission.
14.	Supervisory control	The organization and procedures used to implement communications. This includes the organization of nets, the assignment of frequencies, personnel and equipment, and monitoring the status of communication traffic.
15.	Incomplete message	A message containing some part of the signaling and either none of or only a portion of the information or text.
16.	Priority (two level)	Signaling method of expediting priority messages without interrupting ongoing messages.
17.	Preempt	Signaling method of interrupting an ongoing message to transmit a priority message.
18.	Busy signal	Method of informing a calling station that the called station is busy without interrupting the called stations on-going message.
19.	Hold call	Method of informing a busy operator that he is being called, who is calling him and that he should call back when finished with his current message.
20.	Discrete messages	Messages from one station to one other station in the net.
21.	Conference messages	Messages from one station simultaneously to a number of stations in the net, but not to all net stations
22.	Net messages	Messages from one station simultaneously to all stations in the net.

GLOSSARY (Continued)

23.	Ring-up	Signaling function used to initiate a message from one station to one or more stations in the net.
24.	Ring-back	Signaling function used to acknowledge ring-up.
25.	Ring-off	Signaling function used to acknowledge end of message text.
26.	Station busy probability	The probability that a message is generated at a busy station and/or for a busy station when at least one frequency is not busy.
27.	Operator message cycling	Process of attempting to place a call in a multifrequency net by trying all of the messages in the station's queue until a call is established.
28.	Grade of Service	Probability an operator will encounter a delay when sending a message.
29.	Mean Access Delay	Average time a calling party must wait to send a message given that a delay is encountered.

LIST OF PRINCIPAL SYMBOLS

S	Number of stations in a single net whenever only one net is involved in the discussion.
$S(k)_n$	Number of stations in the k^{th} net of a group of nets.
K	Number of frequencies assigned to a single net or MADA system.
$\lambda(i,j)$	Average number of messages generated for transmission from station i to station j.
$\lambda(i)$	Average number of all messages generated for transmission from station i.
λ	Average number of messages generated by all stations in the net.
$\lambda(i)_n$	Average number of messages generated by net i of a MADA system.
μ_i^{-1}	Average message time duration of i^{th} type of message (i.e., discrete, conference or net).
ρ	Net utilization
$\rho(i)$	Station i utilization.
$\rho(i)_n$	Utilization of net i of a MADA system.
ρ_s	Utilization for the MADA system.
n	Total number of messages in a net.
m	Total number of messages in a station.
P_n	Probability of n messages being in the net at any point in time.
$P_m(i)$	Probability of m messages being in station i at any point in time.
GS	Grade of Service for the net.
GS(i)	Grade of Service for station i.

LIST OF PRINCIPAL SYMBOLS (Continued)

W_A	Mean Access Delay for the net.
$W_A(i)$	Mean Access Delay for station i.
L_q	Average number of messages in the net queue.
$L_q(i)$	Average number of messages in the queue at station i.
W_q	Mean waiting time for a message in the net queue.
$W_q(i)$	Mean waiting time for a message in the queue at station i.